

# Kepler Mission

## Introduction

Since antiquity, people have looked up at the sky wondering about the nature of the countless objects in the heavens. Religious individuals often speculated that the sky held Heaven and the Almighty. On the other hand, philosophers or astronomers were more curious and delved further into scientific and mathematical explanations. A couple of curiosities were the apparent revolution of the Sun around our planet in addition to the bright white dots in the night sky. Eventually, many questions were answered. Galileo, with his telescope, could see far out into the distance of our solar system. Later, Johannes Kepler developed a mathematical approach to explain stellar motions and the way we understand our solar system today. However, as many questions were answered, even more arose that could not be answered at that time.

Modern astronomers were also able to make their own discoveries through advanced technologies including the Hubble Space Telescope (HST). This telescope in orbit about the Earth has captured stunning images of the far distant recesses of our universe. Past discoveries from early astronomers, mathematicians like Johannes Kepler, and today's HST led people to wonder if there could be even more out there. Are there other planets out in the universe orbiting a star not unlike our own Sun? Can planets retain liquid water like our planet Earth? What if some of those planets outside our solar system could support intelligent life as well?

A mission that scientists highly desired was eventually developed to answer many questions about exoplanets. As of 2013, the Kepler Mission has been in progress for a number of years providing solutions to many challenges NASA scientists face, even as Kepler continues to search only quite a small portion of our Milky Way galaxy.

## Historical Background

This mission is named for one of history's revolutionary astronomers and mathematicians, Johannes Kepler. Both the Kepler Mission and its space-based telescope were named in honor of the German astronomer's contributions: his laws of planetary motion and the principle of using Earth's orbit to calculate the stellar parallax to determine the distances of

stars.<sup>1,2</sup> Johannes Kepler did not begin as an independent astronomer. Kepler started under the tutelage of Tycho Brahe, a renowned astronomer in his own right. After Tycho Brahe's death in 1601, Kepler utilized Brahe's extensive data about the motion of Mars to later discover that the orbit of Mars was an ellipse.<sup>2</sup> In 1609, Kepler published a book *Astronomia Nova* describing his results and thus his first two laws of planetary motion:



Figure 1: A portrait of Johannes Kepler

- 1. Planets move in elliptical orbits with the Sun at one focus.**
- 2. A planet's radius vector sweeps out equal areas in equal times.**

Kepler's first law designates that all planets orbit the Sun in an ellipse and not in a perfect circle. They do not orbit around Earth many previously thought. Kepler's second law describes that where the planet's distance from the Sun is great, that planet will move relatively slow, and when

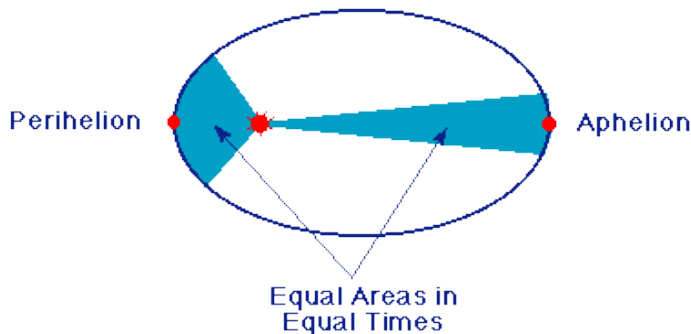


Figure 2: Diagram of a planet in an elliptical orbit demonstrating Kepler's second law.

the distance between the planet and the Sun is short, that planet will move relatively fast. In general, the area covered by the planet roaming at the far end of the ellipse will equal the area covered at the near end of the same ellipse.<sup>2</sup> This is also displayed in Figure 2.

Kepler's third law was not formulated until 1618:

- 3. The squares of the periodic times are to each other as the cubes of the orbital mean distance.**

Kepler's third law of planetary motion indicates that, given in years, one revolution of a planet around the Sun, also thought of as a period, when squared is equal to the cube of the semi-major

axis given in astronomical units (AUs); one astronomical unit is the mean distance between the Sun and Earth.<sup>2</sup>

Although Johannes Kepler is best known for his three laws of planetary motion, there are other astronomy-related discoveries that he presented, each revolutionary within the field. One such discovery is related to Kepler Mission in that he tried finding the distance of the stars from

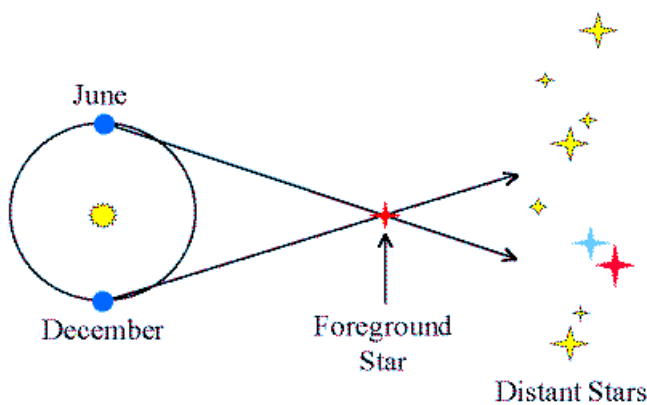


Figure 3: A diagram of stellar parallax demonstrating the visual movement of a distant star from Earth.

Earth using the method of stellar parallax. This is similar to when a person looks at a distant object with their left eye only and then switches to looking at that very same object with only their right eye. The object appears to move when really it is just the different angle that you are seeing it subtend when the angle is small. Instead of using human eyes, the parallax method will employ optical systems and the orbit of the Earth to find the distance of stars.

At one point, an astronomer will observe a star through a telescope, then, a half a year later will do the same thing only now the Earth is on the opposite side of the Sun. This will reveal the distance that star is from Earth through the use of simple trigonometry.<sup>2</sup>

The Kepler telescope applies Kepler's Laws of planetary motion and the parallax method to find new solar systems. However, not only will scientists in this project be utilizing Kepler's laws and principles, but they will also take into account previous discoveries of planets in other stellar systems and use them as a foundation in trying to complete the Kepler Mission. In fact, there are three main planets which were found through ground-based observations by using this information that also contributed to the Kepler mission: TrES-2, HAT-P-7b, and HAT-P-11b.

Of these three ground-based discoveries, the first planet Kepler scientists observed was TrES-2 which has a secondary name of Kepler 1b. About 220 parsecs away from our solar system, TrES-2 orbits Kepler 1, a star similar to our own in mass and size as well as spectral type. Kepler 1 is a G0V and our Sun is a G2V star. TrES-2 is nothing like Earth though. In fact, this planet is bigger than Jupiter. TrES-2 is 1.199 times the mass of Jupiter and 1.272 times Jupiter's radius. This planet is far closer to its star (at 0.03556 AUs) than Mercury is to ours (at

0.387). Comparably, Kepler 1b is practically on top of the star it orbits. It also revolves once around its star every 2.47 days.<sup>3</sup> For the scientists, this was a great start into their ground-based observations.

Further away from our solar system than TrES-2 at 320 parsecs is the planet HAT-P-7b. This planet, also named Kepler 2b, orbits Kepler 2 about 0.0379 AU away. The orbital period of HAT-P-7b is 2.205 days. HAT-P-7b is known to be a super Jupiter as it is 1.8 times the mass of Jupiter as well as 1.421 times the radius. Even though this stellar system is so far away from our own, and the planet is very close to its parent star, scientists were able to determine the average temperature of HAT-P-7b; the temperature is 3160 Kelvin, similar to that of a very cool star partly caused by its closeness to Kepler 2 which has a photospheric temperature of 6350 Kelvin, a temperature greater than our own Sun. Kepler 2 is larger than the Sun (1.991 solar radii) and more massive (1.52 solar masses) too.<sup>3</sup> After these first two observations of stellar systems within our Milky Way galaxy, the scientists begin to find proof that there would be some variety between each system.

The last of the three exoplanets that the scientists discovered was HAT-P-11b, otherwise known as Kepler 3b. This planet is relatively close to our solar system at 38 parsecs. Both the star, Kepler 3, and the exoplanet are different from other systems previously studied by the NASA scientists. Kepler 3 is a star of 0.81 solar masses and 0.75 solar radii. It is also a part of the main sequence star system with a spectral type of K4V and a photospheric temperature of 4780 Kelvin. At about 0.053 AUs from its star, HAT-P-11b has an orbital period of 4.888 days. HAT-P-11b appears different than TrES-2 and HAT-P-7b as it is actually 0.081 Jupiter masses as well as 0.452 Jupiter radii.<sup>3</sup> With three exoplanet discoveries made prior to the Kepler telescope, combined with other contributions from previous projects relative to this subject, the scientists thought they had a good basis for starting on a project such as the space-based Kepler Mission. However, they found that it was going to be a hard and long process before they could get started.

In order to start searching for planets in other solar systems in 1984, NASA Ames Research Center (ARC) first had to figure out what kind of technology was needed in order to detect the transit of a distant planet. Ames Research Center instituted several workshops in an attempt to work with high precision photometry. A few tests in 1987 involved these photometers as the NASA scientists tested silicon photodiodes which were supposed to support them in

detecting other planets. Tests carried out with these photodiodes informed scientists that they had very high precision. However, they still needed to be cooled to near liquid nitrogen temperatures in order to minimize thermal noise. They linked one cooled photometer with the cooled diodes and left the other photometer cooled and unlinked. Then, scientists noted that the photometer connected to the diodes failed its next test.<sup>1</sup> This experiment is one of the more notable out of many that ARC attempts through the next few years.

Eventually, tests that NASA scientists conducted were satisfactory enough for them to start proposing the idea of supporting a program for exploration of planets outside of our solar system. The first proposal came in 1992 when a new line of missions started up. This proposal was to start searching for exoplanets, or more specifically terrestrial planets, through transit detection. When this concept was initially proposed, ARC introduced it as FRESIP (Frequency of Earth-Size Inner Planets); however, the review panel claimed they could not accept this concept as there was no proof that detectors existed with the required precision and low thermal noise despite the worthwhile science that is involved. Instead of being discouraged entirely, the science community encouraged ARC to continue with their project.<sup>1</sup>

In 1994, the FRESIP Mission tried for a Discovery-Class mission. This time, when FRESIP tried for such a remarkable opportunity, they offered a 0.95-meter aperture photometer which used Charge-Couple Device (CCD) detectors instead of silicon photodiodes because of their ability to simultaneously track multiple targets at once and accept various target patterns. FRESIP scientists intended to send it into a Lagrange orbit.<sup>1</sup> This meant that the photometer would be placed in an orbit where certain points throughout its path have gravitational forces equivalent to the photometer's orbital motion allowing the photometer to make revolutions around Earth.<sup>4</sup> The panel reviewing the project considered it to be too expensive for a Discovery-Class mission and thus gave FRESIP their second rejection.<sup>1</sup>

Another proposal was advanced in 1996 by FRESIP scientists when they discovered that costs could be significantly lowered if they have the photometer follow a solar orbit instead of a Lagrange orbit due to how much more space propulsion would be needed to keep the photometer in the Lagrange orbit. At this time the name of the mission, FRESIP, was changed to Kepler in honor of astronomer Johannes Kepler for his laws of planetary motion as well as his principle of the stellar parallax. Although these changes helped the mission be considered a likely candidate, it was not enough as it was never proven whether the photometer could actually detect thousands

of stars simultaneously. It was recommended to build such a device in order to demonstrate that it could be done.<sup>1</sup>

By 1997 the scientists finally built a photometer. They placed this photometer on a refurbished Crocker Dome, and a radio was installed on the spacecraft linking back to a station at Ames Research Center. Software was also installed for control over the dome with the photometer and also to gather data. It took about a year for the ARC to obtain the data made of 6,000 stars in a single field-of-view. Later that same year, Kepler was proposed as a Discovery-Class mission for the third time, its fourth review altogether. The selection committee determined the science to be exceptional with perfectly functioning detectors and a photometer that can discover thousands of stars at a time; however, they found that a photometer could not be developed to prove that it was capable of finding Earth-size planets, especially with the amount of noise it would encounter while in orbit. With this information, a proposal was made for a laboratory demonstration of a star field that will include all noises expected to be encountered in addition to simulated Earth-size transits.<sup>1</sup>

A year later a test bed for Kepler was designed, built, and demonstrated yielding satisfactory results. This led the Kepler Mission to producing another proposal a year later for the fourth Discovery-Class mission, making this Kepler's fifth evaluation. Kepler was one of three accepted out of 26 proposals due to a detailed report of tests completed, and the craft was finally made ready for this mission. At the end of 2001, Kepler was designated as Discovery Mission No. 10. In 2002 the mission started development in order to be ready for launch a few years later.<sup>1</sup>

## **The Kepler Space Telescope and its Mission**

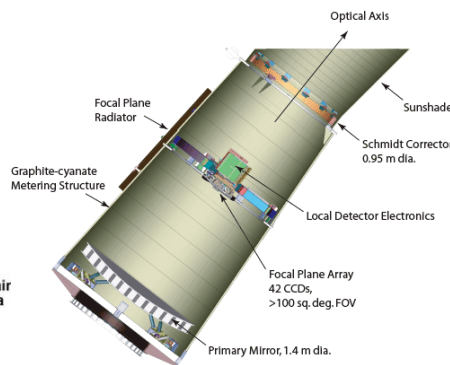
Finally, after years of improvement and then actual development, the Kepler Space Telescope was prepared for the launch and its subsequent mission. This space telescope is an entire spacecraft designed for simplicity and support of one main instrument: the photometer. A few supporting parts of the spacecraft that keep it running are the sunshade which covers the optics from the Sun in order to keep them cold, the star trackers keeping the same stars in the photometer's sight at all times, and the solar array that faces the Sun allowing the spacecraft to remain functional. The spacecraft remains motionless in its orbit except for small reaction wheels

that rotate the entire space telescope so the photometer can point in the same direction while in orbit. This design enhances pointing stability and maximizes power used by the photometer to gather data. The photometer's data will then be transferred into the spacecraft and transmitted to



Figure 4a (left): Diagram of Kepler Spacecraft and its components including the Photometer.

Figure 4b (right): Diagram of Photometer with all elements that make



ground base about once a month.<sup>5</sup>

As the most essential research component of the spacecraft that is displayed by Figure 4a, the photometer requires stability and precision to the highest degree. It is designed with a 0.95-meter aperture and a 105 deg<sup>2</sup> field-of-view (FOV). Only one

instrument constitutes of the photometer: an array of 42 CCDs (charge couple devices). Figure 4b displays where the CCDs are placed demonstrating that these CCDs are not used to take pictures but are defocused to 10 arc seconds improving photometric precision. Each CCD is 50x25 mm and contains 2200x1024 pixels. Because there is so much to observe in just a small section of space, the CCDs are scanned every six seconds from which the photometer only takes out information pertaining to stars that are brighter than visual magnitude 14 to prevent an overload.<sup>5</sup>

Once every design aspect of the spacecraft was set, Kepler scientists finally declared the Kepler Space Telescope ready for launch. Liftoff occurred on March 6, 2009 at 10:49 p.m. EST with no problems taking place. Launching with the space telescope strapped on top, the Delta II rocket soared towards the region designated for the spacecraft to separate and begin its own independent orbit.<sup>6</sup>

After ascent to orbit and detachment from the Delta II, the spacecraft began orbiting the Sun trailing Earth as it went. With an orbital period of 372.5 days, the spacecraft will slowly drift away from Earth in its upcoming years of observation. This is optimal as there will be very minimal disturbing torque reacting on the spacecraft which allows the photometer to keep pointing at the same star field continuously. Also, the photometer needs to be pointed away from

the ecliptic plane in order for it to not be blocked by the Sun or Moon during its course. As the spacecraft orbits the Sun, it experiences a 90-degree turn every three months, the only movement the spacecraft actually undertakes, so that the solar panels can continue to face the Sun while the photometer points in the direction of the selected star field. This is achieved by the small reaction wheels on the spacecraft.<sup>7</sup>

An update about the Kepler Mission was released on January 17, 2013. NASA reported that one of three remaining reaction wheels, the fourth already out of commission on the spacecraft, was using more torque than it should to spin the instrument. This increase in friction was noticed when the spacecraft was about to undergo its quarterly roll. Friction on a reaction wheel is a problem that cannot be left unfixed as it could lead to wearing out to the point of breaking.<sup>8</sup> If this were to occur, then there would only be two reaction wheels left to keep the spacecraft from shifting from its targeted area. There would be a bigger strain on those two wheels. As a result, the Kepler Space Telescope would have to resort to only finding bigger planets as that does not require as much sensitivity.<sup>9</sup> Since the Kepler project team wanted to continue with their original objective of finding Earth-like planets, they decided to put the spacecraft in a “wheel rest” safe mode for ten days so they could provide internal lubrication on the wheel to decrease the friction. During that time, no data was collected and the entire spacecraft was essentially turned off except for rocket thrusters keeping the spacecraft in its correct position. After ten days of maintenance, the Kepler spacecraft was finally operating again and began collecting data once more.<sup>8</sup>

For the Kepler Mission to work, it must monitor all targeted stars continuously. In order to do that, the field of view (FOV) must be in sight at all times for the spacecraft. One requirement for the FOV is that it needs to be outside of the solar system’s ecliptic plane so the telescope will not be blocked by the Sun. Another requirement is for the FOV to have a large number of stars. The Kepler team was able to narrow down their selection to one area along the Cygnus arm of the Milky Way. A region of Cygnus was selected with the spacecraft focused at galactic coordinates (76.32°, +13.5°) or right ascension of 19 hours, 22 minutes, and 40 seconds with a declination of +44° 30’ 00’. This is designated in Figure 5. This region was found to contain about 223,000 stars of various spectral types having a visual magnitude less than fourteen. Of the 223,000 stars, about 136,000 (61%) are estimated to be main sequence stars. From there, the Kepler team cut out 25% of the most active dwarf stars from consideration, thus



decreasing the number to 100,000 useful stars for research.<sup>10</sup> With so many potential stars, the scientists were now ready to observe solar systems along with Earth-like planets that they could hypothetically support.

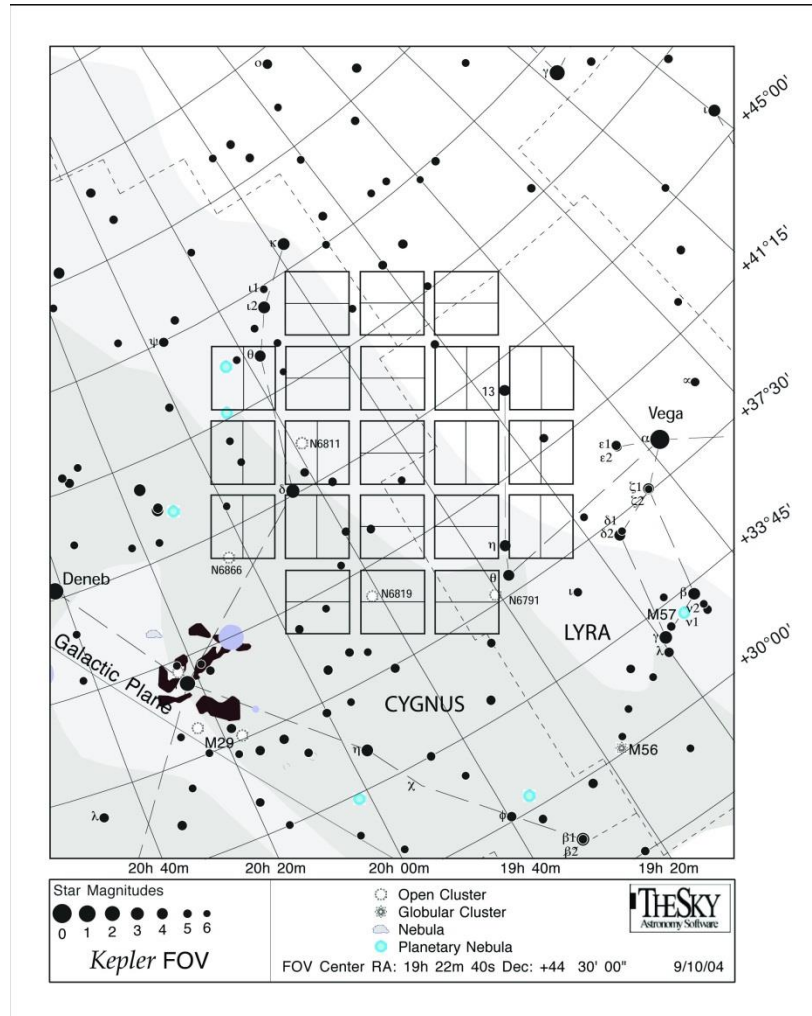


Figure 5: Kepler’s Field of View located in the Cygnus region of the galaxy.

The Kepler team uses a transit method in order to find small planets orbiting their star. The transit method examines the brightness of the star at all intervals of time in order to find out if there are any planets orbiting it. The lifetime of the mission was expected to be about four years long. Scientists expected to detect planets with one-year orbits about four times and planets with about 1.33-year periods, as well as 50% of 1.6-year orbits and 10% of 1.9-year orbits, about three times; predictions are taking into account that these planets are similar to our own, and will be able to get accurate readings on the planets.<sup>7</sup> It was expected that if planets are commonly

found around their stars like our own planetary system, then in locating terrestrial planets with one-year orbits they suspect to discover about 50 planets if they have approximately the same radii as Earth, about 185 planets if they have 1.3 times Earth's radii, and about 12% of located solar systems to have two or more planets. However, they also took into account terrestrial planets having orbits ranging from a few days to more than a year; this way they would not be so limited in their search. Kepler scientists also checked for possibilities of finding giant planets similar to Jupiter or Saturn in size, or possibly even bigger. They claimed that it was expected to find out about 135 giant planets detected inside Earth's orbit, the densities of 35 of those inner-orbit planets, and about 30 outer-orbit planets. Due to the large amount of stars in their FOV, the Kepler team anticipated on finding dozens of more planets outside of the expected terrestrial and giant planets as earlier described.<sup>11</sup>

In general, a transit occurs when a planet crosses between the viewer and the star it revolves around as shown in Figure 6. If it is a transit of one planet, then the change in brightness of the star must be periodic and the amount of brightness displayed during the transit must be the same as well as the length of said transit.<sup>11</sup> Also, for a single planet to transit in front of its star, it must also have an orbital inclination very close to 90°. <sup>12</sup> After observing the change

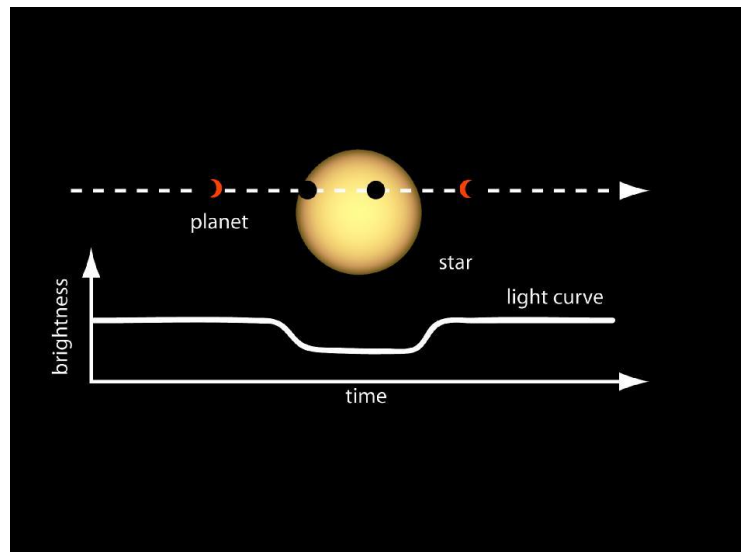


Figure 6: Diagram of a planet transiting its parent star. Underneath is a light curve during the time of the transit.

in the star's brightness, the gathered data can then be analyzed mathematically to obtain more information on the planet and star under surveillance. Once the period of the planet is determined then its orbital size as well as the mass of the star it orbits can be calculated using Kepler's third law of planetary motion. Gathering data on how deep the transit went, or how much the brightness of the star dropped while the planet crossed in front of it, then using that along with the size of the star provides the size of the planet. The planet's average temperature, which is

essential in knowing whether the planet is habitable or not, can be determined by its orbital size and the temperature of the star.<sup>11</sup>

Within the entire universe, about 1 in 3000 stars are suspected to have a planet orbiting it that will travel between its star and Earth.<sup>13</sup> If this proportion is narrowed down to only a portion of the Milky Way, then the 100,000 stars being studied will give the Kepler team that chance to finding those planets. This way, even if Earth-like planets are rare, then finding barely anything will be significant in this search. Since Kepler is searching for terrestrial planets in an orbit relatively close to its star, the aforementioned chances are extremely small also due to the fact that a terrestrial planet only changes a star's brightness during transit by about 1/10,000. Furthermore, their transits generally last between one to sixteen hours at a time. Subsequently, the Kepler team is looking for planets similar to Earth so they are searching for planets with roughly one-year orbits. Given that multiple transits need to be detected for a single planet, this mission is to take about three and a half years.<sup>11</sup>

For a mission such that the Kepler Space Telescope has, it requires a number of people to operate because of the various nuances this mission entails. There are people investigating the data received from Kepler, maintaining the entire mission, sustaining the project so the mission



Figure 7: Portrait of William Borucki, head investigator and scientist of the Kepler mission.

can continue its course of actions, and relating the scientific observations received from Kepler to the general public.<sup>14</sup> In total, there are about thirty co-investigators working on the Kepler mission at NASA's Ames Research Center with a dozen other associates branched off into other areas of expertise as previously mentioned.<sup>15</sup> A few members of the mission that are most prominent are: William Borucki (Figure 7), the Principal Investigator and Chief Scientist who strived to get Kepler established as a mission in the 1990's; David Koch who is a retired Deputy Principal Investigator and worked alongside Borucki since Kepler started; Edward Dunham as Science Team Lead; Natalie Batalha as Deputy Science Team Lead; Roger Hunter as Project Manager; Marcie Smith as Mission Director; and Edna DeVore and

Alan Gould as Education and Public Outreach Co-Directors.<sup>14,16,17</sup> These people, along with others who endeavor in this mission every day whether they are other scientists at ARC,

scientists at a university, or participating scientists from an astronomy organization, all have the same goal in mind: to achieve the goals that Kepler was set to carry out.<sup>18</sup>

Thus far, the primary mission of the Kepler Space Telescope has been inferred. Kepler's primary mission is to find terrestrial planets outside our solar system, specifically planets in the habitable zone where liquid water and life might exist. Kepler is supposed to examine a portion of the Milky Way galaxy to detect Earth-size planets in or near the habitable zone and then resolve how many stars in the entire galaxy will contain Earth-like planets. This will help determine where our solar system stands in a galactic sense. Within the initial mission lies the scientific objectives which the Kepler team wishes to investigate about the structure and diversity of planetary systems. By inspecting thousands of stars, they can:

- Determine the abundance of terrestrial and larger planets 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; and
- Determine the properties of those stars that harbor planetary systems.

For three and a half years, the Kepler team has worked on the mission, and the scientists plan on operating Kepler at least a couple more years on an extended mission.<sup>11</sup>

In spring 2009, the primary mission for Kepler was launched and it ended in fall of 2012. Now with the primary mission over, the extended mission begins which the scientists expect will improve the signal-to-noise situation by combining more transits in order to locate smaller planets, find planets with larger orbital periods, and discover planets revolving around stars that are “noisier” either due to being fainter or having more variability.<sup>11</sup> This extended mission is expected to last as long as four years.<sup>19</sup> Despite the little mishap with the reaction wheel in

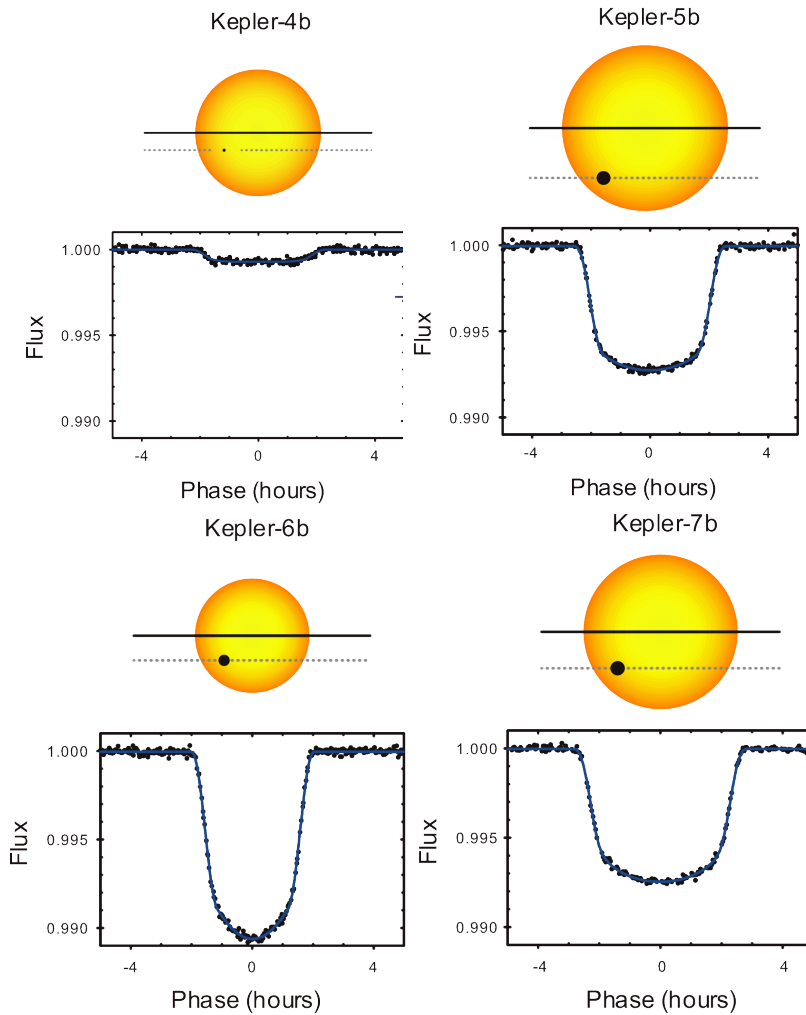
January 2013, the Kepler team trusts that this extension will be even more successful than the already successful primary mission.

## **Kepler's Discoveries**

During Kepler's primary mission, the Kepler team encountered many discoveries that ensured the success of the project as well the guarantee for future exploration. Presently, there are a total of 2740 planet candidates. This means there are 2740 objects that transit their star but further investigation is needed in order to confirm that this object is a planet orbiting its star. Since the mission is ongoing, this number is subject to change as time goes on. This is also true with the number of confirmed planets at 114: further analysis on a planet candidate establishing that it is a planet orbiting a star.<sup>20</sup> Having such an expansive list of exoplanets is not a huge surprise for the scientists at Kepler nor the volunteering scientists at universities. Geoff Marcy, an astronomy professor at the University of California at Berkeley stated that "the Earth isn't unique, nor the center of the universe," expressing what every other scientist is thinking; out of billions of stars in the universe, our solar system cannot be the only one to contain a planetary system. Marcy also comments on the large variety of planets that were discovered, saying, "the diversity of other worlds is greater than depicted in all the science fiction novels and movies."<sup>19</sup>

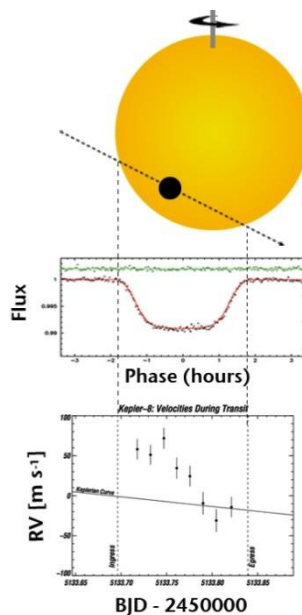
Although it was no surprise to be receiving numerous detections of planets orbiting stars, there was amazement in the diversity of the planets as well as the stars they orbit. Over the past four years the Kepler team made many discoveries but the most notable were of several star systems, planets with a rocky terrain, planets inside the habitable zone, double-star systems, Earth-like planets, planets smaller than Earth, a potential evaporating planet, the concept on small planets in relation to heavy metal stars, red dwarf stars with Earth-sized planets, and a planet smaller than Mercury. These discoveries, among others, helped scientists in their theory of the possibility of a wide variety of stellar systems in only a portion of the Milky Way and allowed them to continue in their search for planets that are similar to our planet Earth.

At the beginning of the Kepler mission many scientists were skeptical about whether or not the spacecraft's photometer would actually receive information on planets outside our solar system. Once the first five exoplanets were discovered and reported in early January 2010, the Kepler team began to look forward to a mission with many successful findings. The first five



Figures 8a (top):  
Light curves of  
transiting planets  
Kepler 4b, 5b, 6b,  
and 7b.

Figure 8b (right):  
Light curve and  
velocities during  
the transit of Kepler  
8b.



exoplanets discovered by the Kepler Space Telescope were Kepler 4b, 5b, 6b, 7b, and 8b. Even though these planets are not Earth-like in any way, as they are known as “hot Jupiters” for their high masses and extreme temperatures, this was a very big step for the Kepler team as these findings “contribute to [their] understanding of how planetary systems form the gas and dust disks that give rise to both the stars and their planets,” as stated by William Borucki after the discovery of these exoplanets.<sup>21</sup> These newly discovered planets range from about Neptune-class to larger than Jupiter with Kepler 4b being the smallest and Kepler 7b the largest of the five.<sup>3,21</sup> Their temperatures span from 2,200 to 3,000 degrees Fahrenheit due to their short distances from their stars. Orbital periods range from 3.3 to 4.9 days. Jon Morse, director of the Astrophysics Division, claimed that they “expected Jupiter-size planets in short orbits to be the first planets Kepler could detect” due to the

short intervals between each transit. It is expected that as the mission moves forward, more planets, smaller in size and with larger orbital periods, will be discovered and eventually lead to the first Earth-like discovery.<sup>21</sup>

In late summer 2010, the Kepler team made another discovery that was the first of many stellar systems like it. This system involves a star, Kepler 9, entangled in a multi-planet system with two planets aptly named Kepler 9b and 9c. As stated, when a planet transits in front of its star the intervals between each transit are periodic. After finding an object that had irregular intervals of transit, they concluded that it could only be two planets with different orbits revolving around one star.<sup>22</sup> This led to Kepler 9b having an orbit of 19.24 days and Kepler 9c of

38.91 days. From their observations, it was noted that Kepler 9b is the larger of the two planets with a radius 0.842 times Jupiter's radius and a mass of 0.252 Jupiter masses. Kepler 9c has a radius of 0.823 Jupiter radii and a mass of 0.171 Jupiter masses.<sup>3</sup> Along with these two confirmed planets, another transition of an object has been discovered which, at the time needing

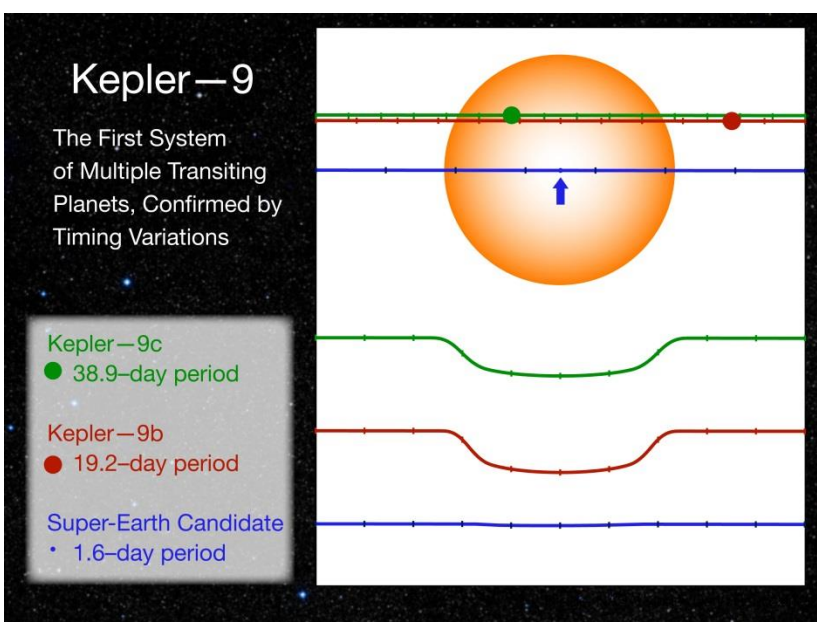


Figure 9: Light curves of Kepler 9 planets transiting their star.

more observation in order to confirm if it was a planet, later becomes known as a super-Earth-sized planet with about 1.5 times Earth's radius and an orbital period about 1.6 days named Kepler 9d.<sup>22</sup> Figure 9 displays the various light curves of the Kepler 9 stellar system. William Borucki, along with other contributing scientists, find the multi-planet star systems predominantly interesting as it is unlikely that so many transits like these would prove to be false readings.<sup>23</sup> The Kepler 9 stellar system in particular contributed more to their interest as it created an opportunity to the measurement of gravitational interactions between planets through observations on the various transition periods; this multi-planet system gives scientists the chance to calculate the mass of planets without using follow-up ground observations through

using the interacting transits. As Jack Lissauer, a planetary scientist at ARC, explains, “the most wonderful discovery of the mission has not been individual planets, but the systems of two, three, even six planets crowded close to their stars, and, like the planets orbiting about our sun, moving in the same plane. Like people, planets interact with their neighbors and can be greatly affected by them. What are the neighborhoods of Earth-size exoplanets like?”<sup>19</sup> Further explorations through Kepler might bring up some answers on Earth-size planets as well as multi-planet systems.

In January 2011, Kepler 10b was confirmed by the Kepler Space Telescope. This is very significant in that it is the first rocky planet ever observed outside our solar system.<sup>24</sup> Even more momentous is that it was the smallest exoplanet found at the time with a radius of 1.4 Earth radii

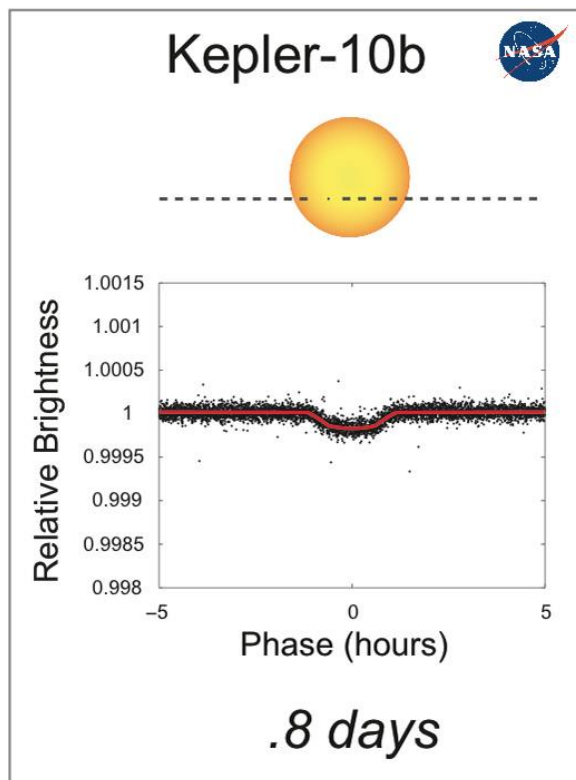


Figure 10: Diagram of Kepler 10b’s light curve as the planet transits its parent star.

but with a mass about 4.56 times that of Earth.<sup>3,24</sup>

It is expected that as Kepler continues its mission, scientists will begin to uncover smaller and smaller planets concluding that small rocky planets could be commonplace.<sup>19</sup> Although Kepler 10b seems to have similar characteristics as Earth, the orbital period is at 0.84 days and orbits its star 20 times closer than Mercury does with the Sun meaning that the planet is not in the habitable zone. Kepler 10, the star that Kepler 10b orbits, was also one of the first stars to be closely observed and suspected to contain a small planet. Once they found Kepler 10b, the information had to be sent to the ground-based observatory in order to confirm that Kepler 10b was actually a small terrestrial planet in orbit.

Doppler shifts that were caused by the pull Kepler 10 had on the planets confirmed their findings. “The discovery of Kepler 10b, a bona-fide rocky world, is a significant milestone in the search for planets similar to our own. Although this planet is not in the habitable zone, the exciting find showcases the kinds of discoveries made



possible by the mission and the promise of many more to come,” states Douglas Hudgins, a Kepler program scientist.<sup>24</sup>

Although the discovery of a multi-planet system has already been construed as substantial when the detection of Kepler 9 was noted, Kepler 11 is even more significant in that not only is it a six-planet system, but these planets orbit very closely to one another around Kepler 11 and are all closer to their star than Venus is to our Sun.<sup>19,25</sup> A month after Kepler 10b’s confirmation, Kepler 11 was confirmed to contain six planets in close orbit as can be seen in Figure 11: Kepler 11b is ten times closer to its star than Earth is to our Sun while the farthest out, Kepler 11g, is half as far from its star than Earth is to the sun. All of Kepler 11’s planets are bigger than Earth

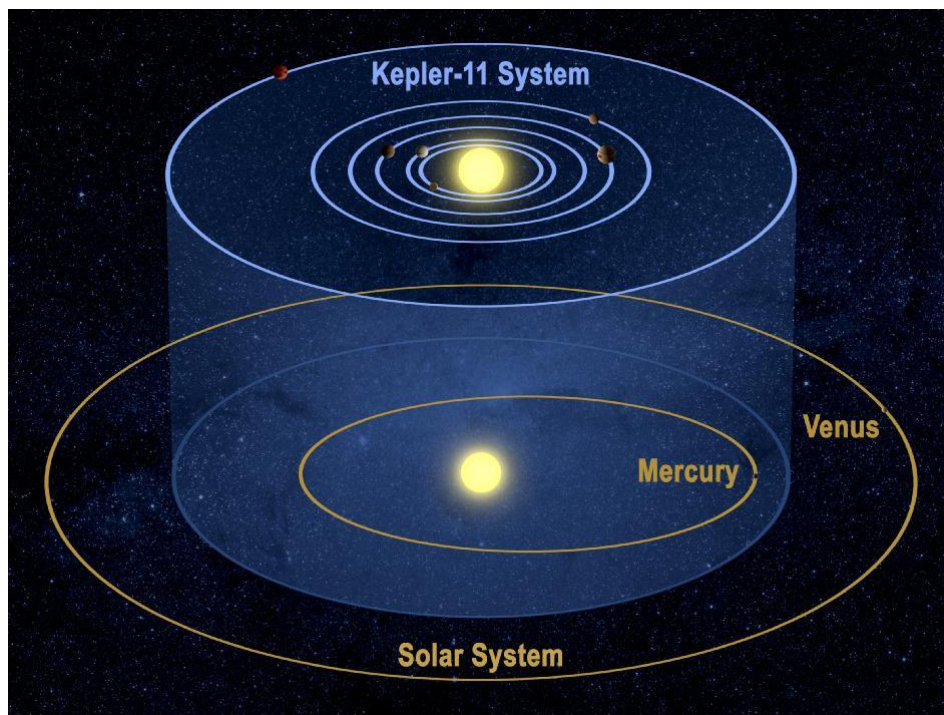


Figure 11: Diagram of multi-planet system comparison between Kepler 11 and our solar system.

with the biggest ones comparable to Uranus and Neptune. Jack Lissauer speaks up again about a multi-planet system as he claims, “Kepler 11 is a remarkable system whose architecture and dynamics provide clues about its formation. These six planets are mixtures of rock and gases, possibly including water. The rocky material accounts for most of the planets’ mass, while the gas takes up most of their volume.” Kepler 11d, 11e, and 11f have are suggested to have formed within a few million years of the system’s formation as they contain a considerable amount of light gas. “By measuring the sizes and masses of the five inner planets, we determined they are

among the lowest mass confirmed planets beyond our solar system,” explains Lissauer as, at the time, this system had the lightest exoplanets that has been confirmed by the Kepler team. Douglas Hudgins is certain that this discovery, among others, will “determine the course of every exoplanet mission to follow.”<sup>25</sup>

About 200 light-years away from Earth, a star system of a “fictional” nature was discovered, or at least many scientists believed it was fictional until they detected orbiting binary stars with a circumbinary planet, i.e. a planet orbiting two stars. By fall 2011, it was confirmed that Kepler 16b was a cold, gaseous, and inhospitable planet about the same size as Saturn orbiting about both stars in a period of 229 days, similar to Venus’s 225-day orbit. Both stars are smaller than our Sun with the larger about 69% the Sun’s mass and the smaller about 20%. These two stars that Kepler 16b orbit tend to transit each other, creating eclipses from our view point. When the smaller star partially blocks the larger star, a primary eclipse occurs and once the larger star completely blocks the smaller star, it is a secondary eclipse. This was what the scientist first noticed about the system, then they found that even when they were not blocking each other, there was still a dip in brightness from the stars: a possibility of a third body. The

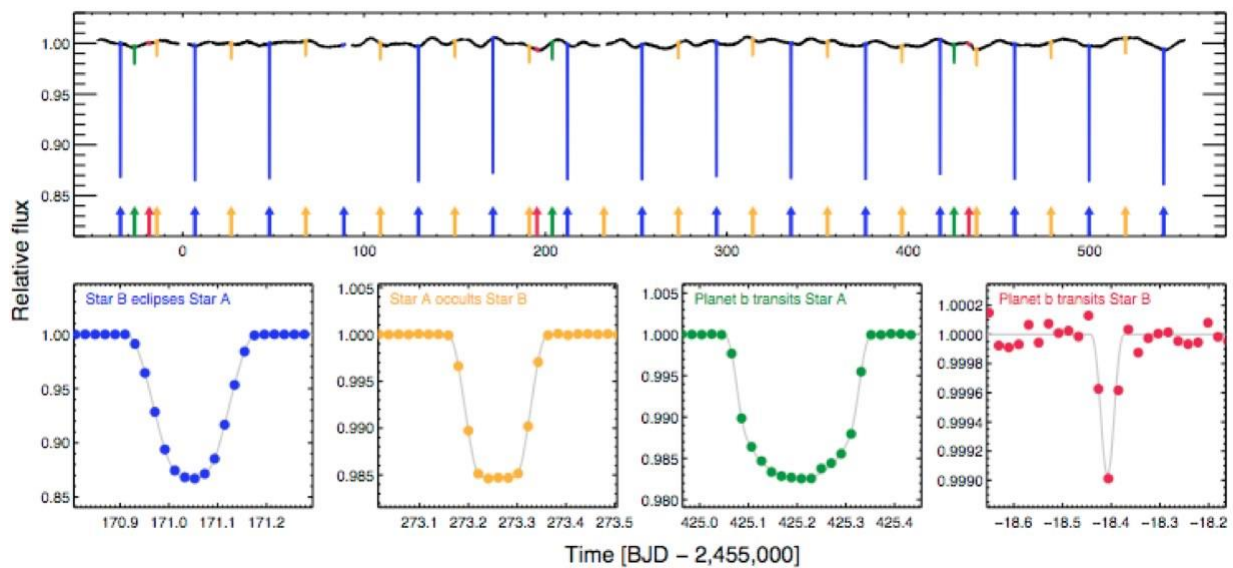


Figure 12: Light curves of the Kepler 16 binary star system.

presence of a third body with some influencing mass was also hinted by the gravitational pull, however small, on the stars, which was measured by the changes in their eclipse times. Kepler scientists were amazed to find Kepler 16b orbiting both stars and not just the one as was suspected in a binary star system. William Borucki said, “This discovery confirms a new class of

planetary systems that could harbor life. Given that most stars in our galaxy are part of a binary system, this means the opportunities for life are much broader than if planets form only around single stars. This milestone discovery confirms a theory that scientists have had for decades but could not prove until now.<sup>26</sup> This, along with other future binary star systems that will be detected, demonstrates that planet can form and survive in a double-star system.<sup>19</sup>

By December 2011, an exoplanet was detected by the spacecraft in an orbit around a star that was located inside the habitable zone. According to Natalie Batalha Kepler 22b is located right in the middle of the habitable zone orbiting a star very similar to our Sun which is also

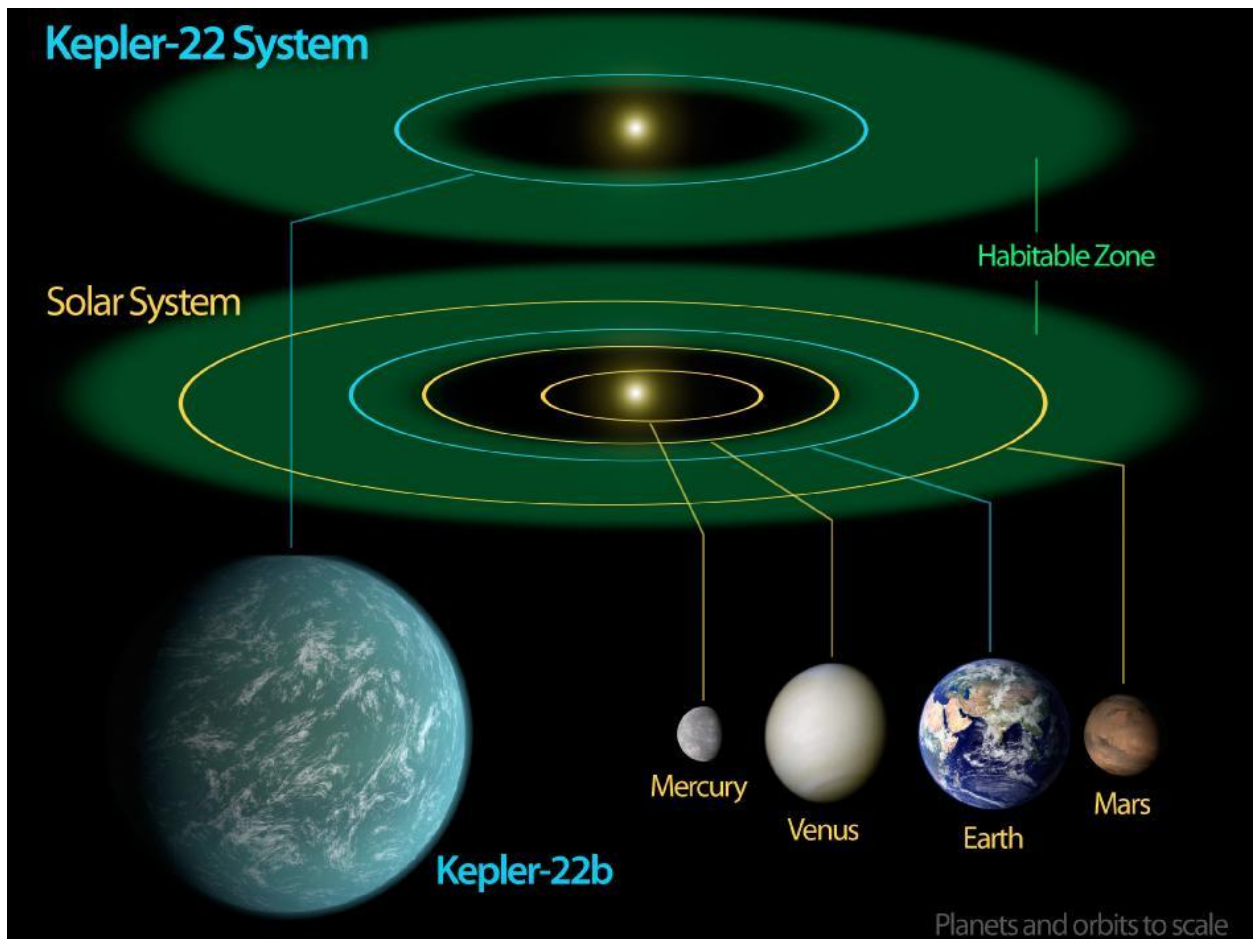


Figure 13: Kepler 22 system compared with the solar system of planets inside the habitable zone.

demonstrated with the comparison made in Figure 13. A few things that could make it a planet like Earth and accommodate life are if it has an atmosphere and a surface that could maintain the liquid water forecasted to be there. William Borucki claims that even if there were no atmosphere, Kepler 22b would still be warm enough to sustain liquid water on its surface: taking

in consideration that there is one.<sup>27</sup> Kepler 22b has similar characteristics to Earth as it is the same distance from its star that Earth is to our Sun, it has an orbital period of 289.8623 days which is relatively close to ours, and is likely to contain water and rock. The only reason scientists are questioning whether it is capable of harboring life is because Kepler 22b is about 2.38 times the size of Earth.<sup>3,27</sup> From just its difference in size, the planet could be Neptune-like in that it had gas and liquid as its “surface” about a rocky core. Kepler 22b could quite possibly be a world completely covered in water. Batahla believes that if this water is like Earth’s oceans, then “it’s not beyond the realm of possibility that life could exist in such an ocean.”<sup>27</sup> At the time of its discovery, Kepler 22b was closest in size to Earth while being in the habitable zone and orbiting a star like our Sun as displayed by Figure 13. Kepler 22b’s discovery confirmed for many scientists that they are getting closer to finding planets like Earth.<sup>19</sup>

While describing Kepler 16b’s stellar system with the planet orbiting two stars, it was implied that there would be more discoveries similar to that one. In January 2012, two binary star planetary systems with each system consisting of one circumbinary planet were established into the Kepler data. Kepler 34b and Kepler 35b are both gaseous, Saturn-size planets orbiting their respective stars. These planets “further establish that such ‘two sun’ planets are not rare exceptions, but may in fact be common, with many millions existing in our galaxy,” as stated by William Welsh, a Kepler participating scientist. He also claims that it “broadens the hunting ground for systems that could support life.” The orbital period of Kepler 34b is about 289 days and the two Sun-like stars orbit one another every 28 days. Kepler 35b orbits its stars every 131 days while the two smaller and cooler stars orbit each other every 21 days. Both planets are located too close to their parent stars to be capable to accommodate liquid water or provide life.<sup>28</sup> These two new confirmations encourage more rummaging of binary star systems which could provide a planet inside a habitable zone and allow more understanding on how a planetary system can survive.

In May 2012 NASA scientists confirmed an unusual discovery out of a super Mercury-size planet that seems to be evaporating due to its proximity to its star. As stated by Jon Jenkins, a Kepler co-investigator for SETI, “the bizarre nature of the light output from this star with its precisely periodic transit-like features and highly variable depths exemplifies how Kepler is expanding the frontiers of science in unexpected ways. This discovery pulls back the curtain of how science works in the face of surprising data.”<sup>29</sup> The parent star (KIC (Kepler Input Catalog)

12557548) is cooler and smaller than the Sun and it was noticed during observations that the light emitting from the star was unusual in that it dropped in various intensities.<sup>29,30</sup> KIC 12557548 b orbits its parent star every 15 hours which is one of the shortest planetary orbits ever observed. This type of orbit is suggested to be very tight and reach temperatures as high as 3,600 degrees Fahrenheit. The varying intensities in light emitted from the parent star were proposed to be because of a slightly amorphous, shape-shifting body. Even though the planet is made of rocky material the temperatures are hot enough for the surface to melt and evaporate with the resulting winds carrying gas and dust into space. Gas and dust trailing behind the planet, similar to that of a comet, along its

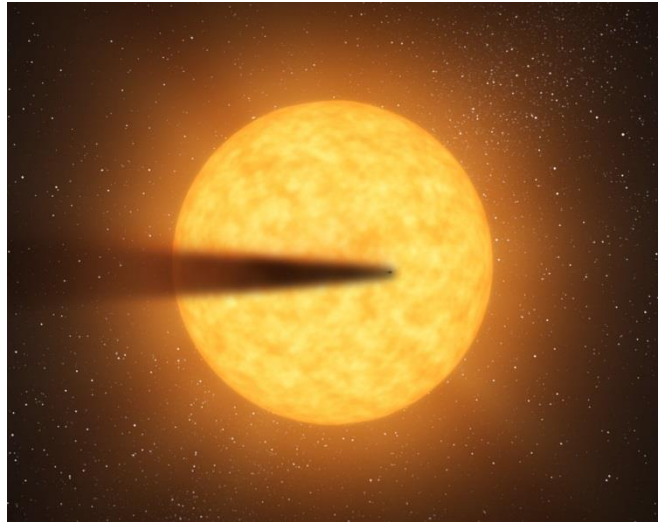


Figure 14: Illustration of evaporating planet transiting its parent star.

orbit is confirmed to be the reason behind the various light intensities during a 15-hour time period. It is theorized that this planet will completely disintegrate within the next 100 million years. “This might be another way in which planets are eventually doomed,” claims Dan Fabrycky, a scientist for the Kepler team, “A lot of research has come to the conclusion that planets are not eternal objects, they can die extraordinary deaths.”<sup>30</sup>

It has been widely thought by many astronomers and other scientists alike that the formation of terrestrial planets could only occur around stars abounding in heavy elements like iron and silicon. By June 2012 scientists were proven wrong when Kepler confirmed its discovery on small planets that were formed around stars containing various heavy elements signifying the possibility of this occurring more often than not throughout the galaxy. A research team at the University of Copenhagen studied the elemental composition of over 150 star encompassing 226 planets smaller than Neptune. Scientists, especially Lars Buchhave who is the leader of the research team, wanted to “investigate whether small planets needed a special environment in order to form, like the giant gas planets, which we know preferentially develop in environments with a high content of heavy elements. This study shows that small planets do not discriminate and form around stars with a wide range of heavy metal content, including stars

with only 25 percent of the Sun’s metallicity.” By ‘metallicity’ Buchhave refers to the stars that have metal content of elements heavier than hydrogen and helium. Giant planets are known to be dependent on a star’s metallicity and are usually formed around metal-rich stars whereas small planets are independent and are now being thought to form around stars with variances in metallicity. Planets up to four times Earth’s size have the ability to form around a parent star containing any amount of heavy elements. After making this discovery on small planets, the new question is whether Earth-size planets require special environments in order to form. Natalie Batalha believes that the “data suggest that small planets may form around stars with a wide range of metallicity – that nature is opportunistic and prolific, finding pathways we might otherwise have thought difficult.”<sup>31</sup>

By the end of summer 2012, scientists already knew of binary systems containing a circumbinary planet. It was first noticed in the Kepler 16 system, but now there is a binary star

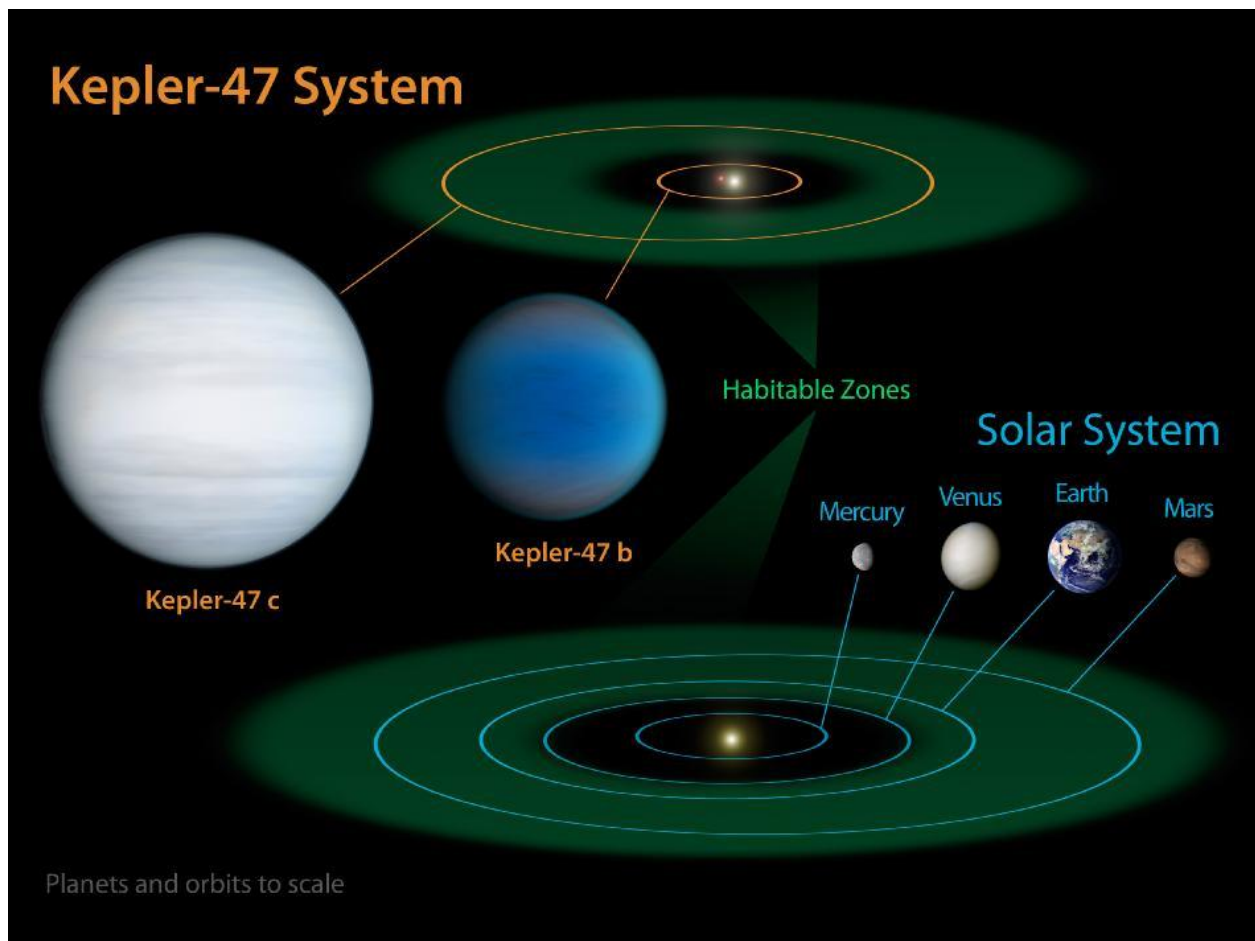


Figure 15: Comparison made of the multi-planet binary star system, Kepler 47, with the solar system.

system discovered to have multiple planets in orbit around the parent stars. The Kepler 47 system hosts a pair of stars that eclipse each other every 7.5 days from Earth's point of view; the bigger star is similar to the size of the Sun, but only about 84 percent as bright while the other star is about one-third the size of the Sun and around one percent as bright. This system was noticed by the transiting planets but, because it is a circumbinary system, the transit itself is a 'moving target' so the time intervals between transits as well as the transit's duration vary greatly. "The intervals were the telltale sign these planets are in circumbinary orbits," states Jerome Orosz, associate professor of astronomy at San Diego State University. Kepler 47b, the planet orbiting closest to the parent stars, makes an orbit in less than 50 days and is about three times the size of Earth, making it the smallest known transiting circumbinary planet. This planet is also hypothesized as a sweltering world with methane inside the atmosphere that could cause a thick haze to cover the planet. Kepler 47c, on the other hand, is inside the habitable zone orbiting the host stars every 303 days. However, the world is figured to be a gaseous giant slightly larger than Neptune with a possible atmosphere containing thick bright water-vapor clouds so it is not likely to harbor life. Proven from the detection of these two circumbinary planets in one system, NASA scientist realize that more than one planet can form and survive in this "stressful realm" thus "demonstrating the diversity of planetary systems in our galaxy." This one finding of multiple planets orbiting a pair of stars opens more doors on discovering habitable worlds.<sup>32</sup>

A majority of the stars in the galactic neighborhood closest to the Sun are red dwarfs. Researchers began to wonder about the red dwarfs because of their proximity to the Sun and the possibilities that have been raised from other discoveries like binary stars with their circumbinary planets: is there the possibility of Earth-like planets forming in a red dwarf stellar system? By early February 2013, these researchers estimated that six percent of red dwarfs throughout the galaxy have Earth-size planets inside the habitable zone. Kepler has analyzed 64 red dwarf stars in its field of view totaling 95 planet candidates. Out of all those planets, only three are considered to be the right size (a little smaller than twice the size of Earth) and temperature for the planets to be deemed Earth-like. These three planet candidates are Kepler Object of Interest (KOI) 1422.02, which is 90 percent the size of Earth in an orbit of 20 days; KOI-2626.01 at 1.4 times the size of Earth in an orbit of 38 days; and KOI-854.01 at 1.7 times the size of Earth in an orbit of 56 days. The planet candidates orbit stars with temperatures between 3,400 and 3,500 Kelvin which is normal for a red dwarf and cooler than the sun (at

5,800 Kelvin). Since red dwarfs are known to be cooler than the Sun, it is also expected to find red dwarf systems with Earth-like planets in the habitable zone have an orbit closer to their host star than Earth is to the Sun. “This close-in habitable zone around cooler stars makes planets more vulnerable to the effects of stellar flares and gravitational interactions, complicating our understanding of their likely habitability,” Victoria Meadows, principal investigator with the NASA Astrobiology Institute, asserts. Questions are raised on whether a habitable Earth-like planet orbiting a red dwarf has the possibility of surviving.<sup>33</sup>

Throughout the entire Kepler mission there have been updates from astronomers on the latest smallest planet discovered in the spacecraft’s field of view. As of late February 2013, the latest smallest planet detected is Kepler 37b which is a part of a multi-planet system (Figure 16).<sup>34</sup> This planet is smaller than Mercury at about 0.303 Earth radii, which is just over the radius



Figure 16: Illustration of planets from Kepler 37 and our solar system showing that Kepler 37b is smaller than Mercury but bigger than the Moon.



of the moon, and orbits its parent Sun-like star every 13.367 days.<sup>3,34</sup> Kepler scientists estimate the temperature of this planet to be more than 800 degrees Fahrenheit. The parent star, Kepler 37, is approximately three quarters the size of the Sun but is considered one of the brightest stars in observation so for such a small planet in close proximity to its host star to be discovered signifies that such small planets like this one are common. Thomas Barclay, a Kepler scientist at the Bay Area Environmental Research Institute adds on, “We uncovered a planet smaller than any in our solar system orbiting one of the few stars that is both bright and quiet, where signal detection was possible. This discovery shows close-in planets can be smaller, as well as much larger, than planets orbiting our sun.” The detection of such a planet also further suggests that all stellar systems are varied throughout the galaxy; therefore, finding a certain type of planet, like an Earth-like planet, could be found in places that scientist might even overlook.<sup>34</sup>

Considering that the Kepler Space Telescope is still searching for planet candidates and the mission itself is still ongoing, there are many more discoveries to make that could answer the multitude of questions scientists are still asking about stellar systems in the Milky Way. If the past four years with Kepler already gave the Kepler team and accompanying scientists so many interesting discoveries, then the next four, or however long the mission will continue, can be expected to provide so much more. As time passes, Kepler is getting closer and closer to locating those Earth-like planets inside habitable zones.

## **Conclusion**

As far as anyone knows, the Kepler mission is heading down the right track in finding Earth-like planets inside the habitable zone. When the project was first introduced approximately two decades ago with Johannes Kepler’s laws of planetary motion and his study on stellar parallax in the back of every NASA scientist’s mind, no one realized how much the Kepler Space Telescope would achieve in its mission observing exoplanets. Of course, back then they figured that, if the photometer was a success in its ability to detect planets in transit with their stars, then they could achieve that next step for humanity in sating their curiosity of other worlds and quite possibly conquer other future projects that come down the road. Kepler’s discoveries of other star systems, rocky planets, planets inside the habitable zone, double-star systems, a potential evaporating planet, the concept on small planets in relation to heavy metal stars, red

dwarf stars with Earth-sized planets, and a planets smaller than Earth assisted NASA scientists in their understanding that there is definitely more out in the Milky Way than what was earlier suspected. If NASA ever gets the chance to benefit from Kepler's findings and use that knowledge on another mission, they would not hesitate in learning more about the universe we live in.

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