Finding Alien Worlds: Studying Exoplanets from Bridgewater State University

Maria Patrone

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Finding Alien Worlds: Studying Exoplanets from Bridgewater State University

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Finding Alien Worlds:
Studying Exoplanets from
Bridgewater State University

by
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in the
Department of Physics

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“Keep Looking Up”

Neil Degrasse Tyson
Bridgewater State University

Abstract

Department of Physics

by Maria Patrone

The search for exoplanets, or planets orbiting other stars in our galaxy, has only been a field of study since the early 1990’s and is currently a popular area of research among astrophysicists. With the launch of the Kepler Space telescope in 2009, there are over three thousand confirmed exoplanets, and over four thousand Kepler Objects of Interest (KOI’s), which are possible exoplanet candidates. With so much data obtained from Kepler, NASA relies on ground based observatories to follow up and confirm KOI’s as exoplanets or false positives. For the last three years I have been studying exoplanets at Bridgewater State University to confirm our ability to observe them using the transit method with BSU’s equipment. I observed and analyzed light curves of exoplanet Qatar 1b and KOI K07525.01, and lay the groundwork for using spectroscopy to rule out false positives.
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Dr. Kling, I was unable to sign your card for you Lifetime Achievement Award, so here it is: Congratulations!!! You are one of the best professors I have ever had, and one of the greatest people I will ever have the opportunity to know! Keep looking up!

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To all in the Universe
Chapter 1

Introduction

1.1 Search for Exoplanets

Exoplanets became a major area of study in 1992 when Aleksander Wolszczan discovered earth size planets orbiting pulsar PSR B1257+12. He made his discovery by observing delays in the time it took for the pulsars pulses to reach Earth (Wolszczan, A. (1994)). Since that initial discovery, there are now 3,711 confirmed exoplanets as of April 11th, 2018 (NASA Exoplanet Archive).

Several initiatives have been dedicated to the search for exoplanets. NASA launched the Kepler telescope on March 6th, 2009. Kepler aimed its sensors to a small patch of sky between the constellations Lyra and Cygnus and observed thousands of stars in a search for exoplanets by looking for small dips in the light coming from the stars. In May of 2013, four reaction wheels broke causing the gyroscope that kept Kepler pointed in the same direction to fail. NASA was able to develop a way to use the photons from the Sun to stabilize the telescope, though its pointing is no longer constant. As a result, Kepler’s re-purposed mission, dubbed K2, gathers data from more sections of the night sky. Due to the mechanics of the telescope, all observations are near the ecliptic, or the path the sun approximately follows over the year (Johnson, M. (2015, March 31)). The patch of sky that Kepler and K2 observes can be seen in figures 1.1 and 1.2.

The ground-based Qatar Exoplanet Survey, in conjunction with the Super Wide-Area Search for Planets (SuperWASP), uses a five-camera CCD imaging system to conduct a wide-angle survey of the northern night sky in search of exoplanets in parts of the sky not observed by Kepler (Alsubai, K. A. et al. (2011)) (Alsubai, K. A. (2014)). The first exoplanet this survey discovered was Qatar 1b with a mass of 1.090 Jupiter Masses ($M_J$) and a radius of 1.164 Jupiter Radii ($R_J$). Its orbital period is 1.42 days and orbits at an
average distance of 0.023 Astronomical Units. Qatar 1b is classified as a Hot Jupiter, and is one of the exoplanet systems we chose to study (Alsubai, K. A. et al. (2011)).

1.2 The Transit Method

There are four ways to detect exoplanets orbiting other stars: the transit method (which Kepler uses), radial velocity, direct observation, and gravitational lensing (Haswell, C.
Of these methods, we are currently most capable of utilizing the transit method at BSU.

In the transit method, the brightness of the host star changes based on the location of the exoplanet orbiting it (figure 1.3). If the star-planet system is oriented in the optimal way, the planet will pass between the star and Earth, partially eclipsing the host star. As the planet passes in front of the star, it will block a small amount of light, making the star dim. To measure this brightness change, we plot the star’s magnitude as a function of time in a light curve (figure 2). We can observe these dips by taking multiple images of the host star during the transit. When the brightness of the star over time is compared with stars of constant magnitude (a method called photometry), we can determine if there is a dip in brightness. Analyzing this brightness dip allows us to determine qualities such as the planets radius, the orbital inclination, and how far away the planet is from its host star. The transit method relies on exoplanets blocking large amounts of light, so it typically favors Jupiter sized planets that orbit close to the host star. As a result, the orbital periods are on the order of days, allowing us to observe a transit every few days.

![Transit Light Curves](image)

**Figure 1.3:** Some of the first exoplanet light curves observed by Kepler taken from NASA.gov (Johnson, M. (2015, March 31)).

### 1.2.1 What A Light Curve Can Tell Us

An exoplanet light curve can be divided into four sections: 1. constant magnitude of the host star, 2. ingress, 3. transit floor, and 4. egress (figure 1.4).

The first (and last) sections of a typical exoplanet light curve are due to unobstructed light coming from the host star. The second and fourth portions of the light curve are generated at the beginning and end of the exoplanet transit. As more of the object passes in front of the star, more light is blocked causing the star to dim. In turn, as
the object stops blocking the star, less light is blocked. The steepness of these sections is affected by the velocity of the object (the faster the object moves, the steeper the curve) and the length of these sections which is affected by the object’s size. The third section, known as the transit floor, is generated when the entire disk of the exoplanet is in front of the disk of the host star. As it transits, the object blocks same amount of light. Sections 1, 2, and 3 give an exoplanet light curve its defining “U” shape.

1.2.2 Exoplanet Light Curve Modelling

1.2.2.1 Piece-wise Function

Modelling a light curve can be done one of two ways: by creating a piece-wise function to approximate each part of the curve, as seen above, or by creating one continuous function that approximates the entire curve. The NASA exoplanet archive uses a model created by Bruce Gary. Gary divides the light curve into seven sections, generating a
piecewise function (his fitting program is openly available on Bruce Gary’s website as a downloadable Excel file (Gary, B. L. (2017)).) Gary’s model takes into account limb darkening of the host star, resulting in additional dimming during ingress and egress of the exoplanet, as well as other effects due to atmospheric and observing conditions (figure 1.5). As a result, Gary’s model includes eight parameters which are:

1. D: The depth at mid-transit
2. $F_2$: The Depth at the end of the ingress divided by D
3. $F_3$: The Depth at the beginning of the egress divided by D
4. $F_p$: The section of the transit in which light is blocked
5. $t_1$: The time at which the ingress begins
6. $t_4$: The time at which the egress ends
7. Air mass Curvature due to changes in the sky condition as the target rises/sets
8. Linear Temporal Trend caused by image rotation

The length of the transit can be found by subtracting $t_4$ from $t_1$.

Bansal D. et al also utilized a piece-wise function to model the flux of starlight in the sections of figure 1.4:

$$f(x) = \begin{cases} 
1 & z[t] > 1 + r \\
F(t) & |1 - r| < z[t] \leq 1 + r \\
1 - r^2 & z[t] \leq 1 - r
\end{cases} \tag{1.1}$$

Where $z[t]$ is a function of time that represents the distance from the center of the star to the center of the planet, and $r$ is the radius of the planet, and

$$F(t) = 1 - \frac{1}{\pi} \left[ r^2 \kappa_0[t] + \kappa_1 - \sqrt{\frac{4z[t]^2 - (1 + z[t]^2 - r^2)^2}{4}} \right] \tag{1.2}$$

$$\kappa_0 = \cos^{-1} \left( \frac{r^2 + z^2 - 1}{2rz} \right) \tag{1.3}$$

$$\kappa_1 = \cos^{-1} \left( \frac{1 - r^2 + z^2}{2z} \right) \tag{1.4}$$
These equations are found using the area of the secant between two circles (Bansal D. et al. (2015)) (figure 1.6). We were able to reproduce these equations as well.

The inclination, or angle of the orbit relative to Earth affects the shape of the light curve. Function $z[t]$ takes this into account with $b$, the impact parameter, or how far the orbit of the planet is from the center of the star. The orbital inclination of the exoplanet affects the impact parameter. As seen in figure 1.7, an inclination of zero degrees will result in no light curve, since the planet does not pass in front of the star at all, while an inclination of 90 degrees will give the signature “U” shaped curve. An inclination somewhere in the middle can remove the transit floor altogether.

### 1.2.2.2 Continuous Function

The Exoplanet Transit Database (ETD) utilizes a continuous function to model light curves. As a result, modelling is quick and easily accessible to web users. The ETD stores the parameters of known exoplanets so users can upload their data, select which exoplanet they observed, and the website will model fit the data - though the input
parameters can be adjusted. This is particularly useful for confirming the quality of one’s own data and this is how we obtained our fit for Qatar 1b. We cannot use this method for exoplanet candidates for which we do not know the planet’s parameters. In an effort to adapt the code used by ETD to help us model exoplanet candidates, we reached out to Ondrej Pejcha, the code’s creator. He responded saying that he no longer worked on the model fit code and gave us an incomplete version of program to try fitting our data with. The code we obtained did not have all the parameters needed to run the function, rendering it unusable (Exoplanet Transit Database.) (Pejcha, O. (2008)).

1.3 False Positives

Not all light curves with dips are due to exoplanets. Other celestial conditions can cause a dip in a star’s brightness such as dust, another star, or the star’s inherent variability. As of April 11th, 2018, Kepler and K2 have found a total of 4,496 exoplanet candidates. This represents an very large amount of data and it continues to grow. To help sort through these data, NASA uses probability analyses as a first pass to see if any of the light curves could be due to an orbiting planet. To do this, they use Vespa, a program created by Timothy Morton, to compare light curves to simulated data and probability distributions of exoplanet systems. If a light curve indicates that a system could be due to an exoplanet, it is designated as a Kepler Object of Interest, or KOI (NASA Exoplanet Archive).

After going through the statistical analysis, NASA relies on ground based professional and amateur observatories to gather more data on potential exoplanets systems. Observers generate their own light curves of KOIs and analyze them to try and determine whether the exoplanet candidate is a false positive or an exoplanet system. Techniques used to exclude false positives due to multiple star systems utilize spectroscopy. Stars of different temperatures can be differentiated by their spectra. For example, cool stars will have thicker metal spectral lines. Hot stars will have strong hydrogen lines, but the hottest stars will have all faint lines as most of their electrons have ionized. When two different spectral type stars are in a binary orbit, the spectrum will show both stars’ spectra imprinted on top of each other, as illustrated in figure 1.8.

If a system’s spectrum does not support a multiple star system, we can further test the possibility of the presence of an exoplanet by utilizing the radial velocity method. This method uses spectroscopy to observe Doppler shifts of the host star. Stars and planets orbit around a center of mass rather than the center of the star. With most exoplanet systems, this center is still inside the body of the star, causing it to “wobble” as the
planet orbits around it. When the star wobbles away from us, its light becomes slightly redshifted, and when it wobbles towards us, the light becomes slightly blue shifted. Figure 1.9 shows how the Hydrogen Balmer lines would be affected by radial velocity. By analyzing how much of a shift is created, the planet’s radial velocity towards and away from us can be calculated (Haswell, C. A. (2010)). The equation for the Doppler Shift is as follows:

\[
\frac{\Delta \lambda}{\lambda_0} = \frac{v}{c} \tag{1.5}
\]

\[
\Delta \lambda = \frac{v \lambda_0}{c} \tag{1.6}
\]

where \(v\) is the velocity of the object, \(c\) is the speed of light, and \(\lambda\) is the wavelength of the light. Since the object’s velocity and the change in wavelength are proportional, when the velocity of the object increases, so does the wavelength shift. The shift is also proportional to the rest wavelength – shifts will be longer toward the red end of the spectrum, and shorter toward the blue.

### 1.4 Past Exoplanet Research at Bridgewater State University

Exoplanet research has been a popular research topic at Bridgewater State University since 2012. The first project was done by Katie St. Laurent when the new Math and Science building first opened. Her exoplanet research used remote telescope viewing to observe light curves of known exoplanets rather than equipment from BSU. Instead, St. Laurent used the Sonoita Research Observatory in Arizona and the Grove Creek Observatory in Australia to study the known exoplanet CoRoT 2b. She was able to
Figure 1.9: Example how the orbital position of a star and orbiting object can affect the star’s spectrum. (Hydrogen Balmer Lines used)

Figure 1.10: The data St. Laurent got on CoRoT – 2b. Note how while it is only half the transit, the data is clean with small error bars (St. Laurent, K. (2012)).

In 2013 Talia Martin continued exoplanet research using Bridgewater State University’s fourteen-inch Celestron Schmidt-Cassegrain telescope. Using a Canon Rebel Ti Digital Single Lens Reflex (DSLR) camera, Martin observed HD 189733b and was the first to successfully observe and generate an (albeit noisy) light curve for a known exoplanet from Bridgewater State University, as seen in figure 1.11. Ultimately Martin determined that a DSLR camera is not the ideal camera to use and proposed that a CCD camera should be used for exoplanet research instead (Martin, T. (2013)).

I started my own exoplanet research in 2015. Building off of St. Laurent’s and Martin’s work, I started by imaging known exoplanets with a research grade Charged Couple Device (CCD) camera. This work is the basis for this thesis.
Figure 1.11: The data Martin got on HD189733b. Note that while there is a slight dip during the transit, the data are very messy with large error bars. The bottom graph shows the data with the upwards trend due to the atmosphere removed. The x-axis is time in Julian date and the y-axis is relative magnitude (Martin, T. (2013)).
Chapter 2

Methods

2.1 Observing Equipment

2.1.1 Telescope and Mount

Figure 2.1: An image of our research telescope. The blue box at the back end of the telescope is the CCD camera and the black circle attached to it is the filter wheel.

All of our data were gathered using BSU’s fourteen-inch Celestron EdgeHD Schmidt-Cassegrain telescope on a Paramount ME Robotic Telescope System (figure 2.1.)
2.1.2 Imaging

Data images were taken with an Apogee Alta U47 CCD camera cooled to -15 degrees Celsius. The CCD camera chip size is 1.3321 cm², has a U47-UV coating, and has a field of view of 12 arcminutes. The U47-UV coating makes the chip more sensitive to light in the ultraviolet range (Apogee Alta Series) (figure 2.2). With our optics and correct sky conditions, we can see down to magnitude 20 - any lower and the signal to noise ratio is too low.

Figure 2.2: A graph representing the sensitivity of our CCD Camera. The blue line represents the U47-UV coating that our chip has (Apogee Alta Series).

2.1.3 Filters

Our filter wheel is an Apogee FW50-9R series containing a red, blue, clear, ultraviolet, infrared, and luminance (clear) Johnson Cousins filters. The sensitivities of each filter are shown in figure 9. The peak wavelength for red filter is 634 nm and the clear filter lets all light through to the camera sensor (Hanschur, U. (2017, January 30)). A graph of where all the peak wavelengths of the Johnson Cousins filters can be seen in figure 2.3. The red filter transmits red light which is least impacted by atmospheric scattering; as a result, as a star system moves across the sky over the course of an evening, we do not have to worry as much about atmospheric effects.
In our filter wheel we have a Shelyak Star Analyzer 200 diffraction grating. The grating is a 200 lines per millimeter transmission grating and has a diameter of 1.25 inches. Figure 2.4 is an image of what the filter looks like.

In our filter wheel we have a Shelyak Star Analyzer 200 diffraction grating. The grating is a 200 lines per millimeter transmission grating and has a diameter of 1.25 inches. Figure 2.4 is an image of what the filter looks like.

Figure 2.3: A graph representing the sensitivity of each Johnson Cousins filter (Hanschur, U. (2017, January 30))

2.2 Object Selection

Before we attempted to observe exoplanet candidates (KOIs), we chose to observe the well documented exoplanet Qatar 1b so we could test the Apogee CCD capabilities with our telescope set up and location. Because Qatar 1b is a known exoplanet, we subsequently were able to use the ETD model fitting program to test the quality of our data. Once we determined we could make reliable exoplanet light curves, we moved on to observe a KOI.

We chose Qatar 1b (and the KOI) using the following criteria:

- Targets needed to have a magnitude brighter than 19 to be detected by the CCD camera.
- The depth of the transit had to be greater than 0.02 magnitude, otherwise it would be lost in the noise and not be observable.
• The transit needed to occur after the Sun had completely set.

• Bridgewater is in a heavily populated area, with a lot of light pollution. As a result, we chose targets that transited at an altitude higher than 40 degrees, allowing us to shut the lower dorm shutter, cutting down on the light pollution. We also made sure all lights, no matter how small, were turned off or covered in the dome.

With all these constraints, the list of KOIs was small and we chose K07525.01 because it had the most transits during the summer of 2016.

2.3 Observations of Qatar 1b and K07525.01

The NASA Exoplanet Archive’s Transit and Ephemeris Service provided the transit times for both Qatar 1b and K07525.01 for our latitude (42 degrees North) and longitude (71 degrees West). To observe a sufficient portion of the host star’s flat light curve, we observed an hour before the transit until an hour after the transit ended. Data images were 30 second exposures and taken with red and clear filters. We alternated between the two filters over the course of the transit – otherwise, if we had taken all the red images first then the clear, we would only have half of the transit in each filter. Dates and other information of the observations of Qatar 1b and K07525.01 can be found in table 1.

Our university receives Massachusetts NASA Space Grant Consortium funds to support a group of students who do astrophysics research. The group is called the Bridgewater State University Experimental Astrophysics Research (BEAR) Team, and I have been part of it since its inception. Students work in teams to take data every clear night. The data the team collects can be used by anyone at BSU ad have been used for projects in 100 level astronomy courses as well as individual projects like this thesis. The BEAR team maximizes BSU’s ability to utilize our research grade equipment. Much of the data taken for this thesis is due to the BEAR team.

2.4 Image Calibration

Each night, before imaging a transit, we took dark, flat, and (sometimes) bias calibration images. These images are used to process out any noise that occurs in the data image.

• Flats are used to subtract out dust and other impurities in the optical path of the telescope and camera. Flats are taken during twilight on an evenly lit sky. We take
twelve images ranging between 1 and 1.7 seconds for each filter in the luminance (clear), Blue, Green, and Red filters with count levels between 30% and 55%. Any count levels outside this will result in extra noise in the images. Twelve flats are taken in each filter every night.

- **Darks** are images that are the same exposure length as the flats and data images but are taken with the camera shutter closed. These subtract out the thermal noise generated as the camera is taking an image. Twelve darks are taken for each exposure time every night.

- **Biases** are images taken with a zero second exposure. These images are used to subtract out the electronic noise that is created just by the image being taken, sent through the wires to the computer, and downloaded. 50 biases are taken every six months.

All CCD data image calibration was processed using the software MaxIm DL 6. First the flats were calibrated by subtracting the matching darks and biases. We then subtracted the calibrated flats from our images. Both of these calibration steps used the sigma clip setting, which averages the count of each pixel but disregards any outliers. An uncalibrated and a calibrated image are compared in figure 2.5.

![Figure 2.5: An unprocessed (left) and a processed (right) image to show the difference image processing has on the data. Note the removal of dust and smoother background.](image)

### 2.4.1 Imaging Issues

Even after calibration, dark rings caused by pieces of dust in the path of the optics may still remain in the images. The dust can be in the scope, on the mirror, or on the camera chip. While they are meant to be taken out during the flat calibrations, increasing the contrast of the image shows that there can often still be vestiges of particularly large
and dark ones. Note that these spots are taken into account when choosing the check and reference stars for photometry.

In the spring of 2017, we noticed all of our images had a “starfish” like pattern around the edges. This pattern caused parts of the image to be artificially darkened, making the magnitudes of the stars unreliable, especially compared to those stars not in the pattern. We determined this was caused by the camera shutter not opening completely. We expect this effect to be present in images with exposure times less than 0.003 seconds, however there was no reason it should be showing up in images with exposure times between 1 and 30 seconds. (See figure 2.6 for an example of residual dust rings and the starfish pattern.) We concluded that the shutter of the camera was damaged and sent it back for repairs. When the camera was returned to us, the shutter problem was fixed, and they had also cleaned some dust that was on the chip, allowing us to have must clearer images. This repair did impact our ability to collect more data, however.

### 2.5 Photometry

Once the images are calibrated, they are ready for photometry. Photometry is the process of analyzing the magnitude of an object over a period of time. We used MaxIm DL to do this as well.

To find the magnitude of the star we are interested in at any given time, we compare it to the magnitude of a “reference” “check” star that is also in the telescope’s field of view.
view. The reference star is the star that will ultimately be checked against the target star. Since we cannot easily calculate the star’s absolute magnitude, rather the relative magnitude that the instrument reads, we must compare stars within the same field of view to see how their magnitude changes. Check stars are not directly compared with the target star, but are rather compared to the reference star to determine whether the reference is a usable one or not. Since MaxIm DL subtracts the magnitudes of the target object from the reference star, we must make sure the reference star has a straight, constant light curve. The check stars are used to determine this, which will be detailed further below.

To help find reference stars, we use American Association of Variable Star Observer’s (AAVSO) star plotter function which allows us to input the host star’s right ascension and declination, desired maximum magnitude, as well as the telescope’s field of view. We generated charts with a field of view of 15 arcminutes, giving us more room to find patterns of stars to cross reference with the actual data images (figure 2.7). Due to our equipment magnitude limit of 20, we set the star plotter to only show stars 20 magnitude and greater. Note that the numbers shown in figure 2.7 that are attached to some stars are check stars that the AAVSO recommend. The red circles are the object we are observing, the green is the reference star, and the blue are the check stars we chose.

![Figure 2.7: Star charts used to find Qatar 1b and K07525.01. The star to be observed is in the center of the image circled in red. Check stars we used are circled in blue and the reference star is circled in green. (Variable Star Plotter)](image)

After data images were calibrated, we identified the target object and reference and check stars. To compare magnitudes of stars, we need to first subtract out background light. We determine background rates by defining a region (or annulus) close to the star free of any other stars. Figure 2.8 shows an inner, middle, and an outer ring. These three circles can all be size adjusted to fit the star and define the background area. The inner circle, or the aperture, is where the object we are interested is centered. This...
The section measures the counts of all pixels inside the circle. The middle ring surrounds a region called the gap. This region is an area of the image not used in photometric analysis, and instead helps ascertain that another star or object does not artificially brighten the target object or the background. The background count is determined using the region between the middle and outer ring, or the annulus. This annulus covers a flat background with an even noise level. The average counts measured in this ring are subtracted from the pixel counts in the aperture. Figure 2.9 shows how the photometry tool is placed in an actual data image.

The next step is to compare the brightness of the object of interest with constant intensity stars. Unfortunately, not each field of view contains known non-variable stars. Therefore, we choose some that may be good candidates and plot their magnitudes over the course of the observation period. A perfect reference star will not change magnitude over the course of the night, so its light curve will be a straight line. An image of a good reference star can be seen in figure 2.10. When zoomed in, we can see the exoplanet dip in figure 2.11. To find a good reference star, the reference candidate is compared to two other “check” stars. To find the best reference star in the field, we look for little to no variability in both check stars and the reference. Since the reference star is automatically zeroed by the software, if the same variability shows up in the same spot on all three light curves, then the variability is actually in the reference star, as seen in figure 2.12. The star that makes straightest light curve in the check stars is then used as the reference star. The magnitude of the object of interest is subtracted from the magnitude of the reference star and this final count is the relative magnitude plotted in an exoplanet light curve.
Figure 2.10: A MaxIm DL graph displaying the light curves of a good reference star, Qatar 1b, and two check stars.

Figure 2.11: A zoom in of the Qatar 1b light curve. Zoomed in one can make out the prominent transit dip.
Figure 2.12: A MaxIm DL graph displaying the light curves created by a bad reference star. Note how all three graphs have similar rises and dips.
Chapter 3

Data and Analysis

3.1 Table of Observed Objects

<table>
<thead>
<tr>
<th>Exoplanet/KOI</th>
<th>Dates Observed</th>
<th>Filters</th>
<th>Exposure Time (seconds)</th>
<th>Orbital Period (days)$^1$</th>
<th>Transit Depth (mag)$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qatar 1b</td>
<td>10/11/15</td>
<td>Red, Green</td>
<td>30</td>
<td>1.42002</td>
<td>0.02140 ± 0.00</td>
</tr>
<tr>
<td></td>
<td>11/17/15</td>
<td>Red, Clear</td>
<td>90</td>
<td>420±</td>
<td>022 ± 019</td>
</tr>
<tr>
<td></td>
<td>6/14/16</td>
<td>Red, Clear</td>
<td>30</td>
<td>0.00000</td>
<td>022 ± 019</td>
</tr>
<tr>
<td></td>
<td>6/18/16</td>
<td>Red, Clear</td>
<td>30</td>
<td>420±</td>
<td>022 ± 019</td>
</tr>
<tr>
<td></td>
<td>11/22/16</td>
<td>Diffraction</td>
<td>30</td>
<td>4e-08</td>
<td>000165</td>
</tr>
<tr>
<td>K07525.01</td>
<td>7/2/16</td>
<td>Clear, Red</td>
<td>30</td>
<td>0.50245</td>
<td>0.0374 ± 543±0.0</td>
</tr>
<tr>
<td></td>
<td>7/5/16</td>
<td>Clear, Red</td>
<td>30</td>
<td>4299±</td>
<td>0.0374 ± 543±0.0</td>
</tr>
<tr>
<td></td>
<td>7/12/16</td>
<td>Clear, Red</td>
<td>30</td>
<td>4e-08</td>
<td>000165</td>
</tr>
<tr>
<td></td>
<td>7/13/16</td>
<td>Clear, Red</td>
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<td>4e-08</td>
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<tr>
<td></td>
<td>11/22/16</td>
<td>Diffraction</td>
<td>30</td>
<td>4e-08</td>
<td>000165</td>
</tr>
</tbody>
</table>

Table 3.1: Parameters of objects observed as well as information on data taken from Bridgewater State University. Object parameters taken from the NASA Exoplanet Archive (NASA Exoplanet Archive).

3.2 Qatar 1b

On October 11th, 2015, Qatar 1b had a transit from 3:23am UT to 5:11am UT. We observed an hour before until an hour after in the filters clear and red. Once the data were processed, and a suitable reference star was identified, we uploaded our data to the Exoplanet Transit Database (ETD) and model fit it.

$^1$NASA Exoplanet Archive
Figure 3.1: Light curve of Qatar 1b produced by the Exoplanet Transit Database. The x-axis is time in Julian Date and the y-axis is relative magnitude.

Figure 3.1 is the EDT generated light curve with our data from the transit of Qatar 1b in the clear filter. The top graph is the original data taken by us and the bottom is our data with the linear upwards trend removed. The linear trend is created by the star moving across the night sky - as it moves, the star’s light will come through different amounts of the Earth’s atmosphere, artificially brightening or dimming the magnitude of the star. Error bars were calculated using the following equation:

\[ \text{Error} = \sqrt{(\text{ObjectMagError})^2 + (\text{ReferenceMagError})^2} \]  

(3.1)

According to the existing data from the Exoplanet Transit Database, the transit depth of Qatar 1b should be 0.0204 magnitude with a transit duration of 96.7 minutes. The ETD model fit to our data showed we observed a transit depth of 0.0236 ± 0.0015 magnitude and an transit duration of 97.6 ± 3.4 minutes. Our data is comparable to that of published data.

On November 17, 2015, we imaged Qatar 1b again. The focus however, was completely off, making the image impossible to analyze, even after calibration; Maxim DL was unable to recognize any stars in the images. An image of what the data images look like is in figure 3.2.

On June 14, 2016, the MaxIm DL feature “group by slot” was mistakenly selected such that the filter color images were group in a way that the light curve lost resolution as a result (figure 3.3).
On June 18, 2016, we imaged Qatar 1b when it was not in transit to determine if the host star was variable. We determined it was not.

### 3.3 K07525.01

Data for the KOI K07525.01 were taken on July 2 EDT (July 3 UT) 2016 from 1:33am UT to 5:53am UT. The transit itself took place from 2:33am UT to 4:53am UT. We observed the transit from an hour before it started to a half an hour after. The most
prominent attribute of the KOI graph is that it takes on a distinct “V” shape, compared to the “U” shape of the known exoplanet (figure 3.4).

Figure 3.4: Our light curve for K07525.01 on July 2 2016 in the clear filter. Note the “V” shape formed by the data.

On July 5th, 2016, from 2:02am UT to 5:00am UT we again observed the ”V” shape of K07525.01’s light curve. (figure 3.5)

Figure 3.5: Light curve of K07525.01 on 7/5/16.

On July 12 EDT (July 13 UT), 2016, from 2:58am UT to 6:25am UT we observed K07525.01 - and saw the ”V” shape once again (figure 3.6).

On July 13 ETD (July 14 UT), 2016, from 3:04am UT to 6:46am UT, we observed K07525.01. Near the end of the image run, clouds partially covered the sky, artificially changing the magnitude of the KOI (figure 3.7).

We were confused at first about the shape of this light curve, but when we compared our data to those from the NASA Exoplanet Archive’s Transit Crossing Event Review Team (TCERT) Report, we found that they also observed the “V” shape. Their data includes two humps at the beginning and end of the transit, a feature that we found in
our data as well. The light curve in Figure 3.8 is created by overlaying the data form many transits on top of each other. The odd curve is the secondary transit created when the object passes behind the star.

We proposed two hypotheses that could explain the observed “V” shape:

1. The exoplanet is not fully passing in front of its host star, so its entire shadow is never apparent, as seen in figure 3.9.

2. K07525.01 is not an exoplanet at all, but rather a binary star system. In this case, the object is fairly large compared to its host star and is more likely to be in the egress by the time it reaches maximum depth.
Figure 3.8: Data from the NASA Exoplanet Archive’s TCERT Report on K07525.01 (NASA Exoplanet Archive).

Figure 3.9: A hypothetical planet forming a “V” shaped light curve.

With our technology, we do not have the ability to further test the first hypothesis, but we could possibly test the second hypothesis with spectral analysis.

To see if our existing equipment was capable of producing high enough resolution spectra, we used the Star Analyzer 200 diffraction grating in our filter wheel and the software RSpec to obtain a spectrum of the known binary system Algol (figures 3.10 & 3.11).

We in fact were able to observe a black body spectrum for Algol and decided to obtain a spectrum from K07525.01. On November 22, 2016, we observed K07525.01 with the diffraction grating. Unfortunately, the field was too crowded with stars for the program to produce a black body curve or any spectral lines for our object of interest (figures 3.12 & 3.13).

As a result of this experiment, in order to increase resolution, and focus in on just the KOI, we bought a Baader Planetarium Echelle Spectrograph. We devoted many hours to
setting it up and understanding how it worked. Unfortunately, there were some defects in the instrument so it was gone for several months getting repaired, which impacted our ability to get spectral data from K07525.01.

When researching how others observed an exoplanet’s radial velocity, we found that an exoplanet would only make a shift in the spectrum by a few angstroms. Unsure if we could observe a change this small at BSU’s location, we came up with a list of possibilities for what we could determine when we do get observations.

- If we observe overlapping stellar spectra, we can conclude that K07525.01 is a binary star system.
Figure 3.12: Image of K07525.01 through our diffraction grating. The KOI and its spectrum are encircled in red. Note how stars are over the spectrum of the KOI, artificially brightening it.

Figure 3.13: Spectrum of K07525.01 in RSpec with the Hydrogen Balmer lines and a type A star spectral lines overlaid. Note how no black body curve is seen and no significant dips are found.

- If we observe a shift but no overlapping spectra, there is a high probability we have observed an exoplanet.

- If we observe no shift, we can conclude that K07525.01 may an exoplanet system with a shift in its spectrum too small to see through the light polluted atmosphere of Bridgewater State University.

3.4 K03810.01

With the success of observing the light curve of K07525.01, we decided to observe other KOI’s concurrently. The Kepler Object of Interest K03810.01 was observed on March 12
2017. It was during this time, however, that we noticed deformities in the data images. Upon closer inspection of all data images taken during that time, we found that the shutter of the CCD camera was not opening all the way during the exposure time, thus rendering all data images from spring 2017 unusable. The camera was sent back to be repaired and so more data was taken in spring 2017. A data image with of K03810.01 can be seen in figure 2.6.
Chapter 4

Conclusions and Future Work

When beginning this research in 2015, our goal was to learn techniques for observing and analyzing exoplanet light curves from Bridgewater State University (BSU). Our first success came when we used a CCD camera to successfully observe Qatar 1b. With this knowledge we expanded our data collection and analysis to Kepler Objects of Interest (KOI’s). We were able to observe them, but realized we needed to do more to confirm their exoplanet status. In the process, we learned valuable lessons about how to observe using the transit method, such as how to understand what each part of the light curve means, how to date data images with low noise, and how to chose the perfect KOI to observe for BSU’s sky conditions. We also made some progress on learning different modeling techniques, but that turned out to extend beyond the scope of this project.

With the acquisition of the Baader Planetarium Echelle Spectrograph, BSU’s next step will be observations of known binary stars, known exoplanets, and KOI’s. The ultimate goal will be to be able to quickly and accurately use our equipment to confirm whether a KOI is either an exoplanet or a false positive.

With more data coming from telescopes like TESS and other exoplanet search missions, BSU students should have plenty of opportunities to build off the work presented here to make their own contributions to the search for exoplanets. Who knows - it may be a current or future BEAR team member who confirms that a KOI is an exoplanet!
Chapter 5

References


• Martin, T. (2013). Determining the Exoplanetary Research Capabilities of Bridgewater State University.

• NASA Exoplanet Archive. (n.d.). Retrieved February 05, 2018, from https://exoplanetarchive.ipac.caltech.edu/


• Shelyak Instruments — Vous ne verrez plus les étoiles ... (n.d.). Retrieved from https://www.shelyak.com

