Draft version June 14, 2023
Typeset using LaTeX default style in AASTeX631

PHYS134L: Finding WASP-14b with Transit Photometry

[1] Department of Physics, University of California, Santa Barbara, CA 93106

(Dated: June 14, 2023)

ABSTRACT

This paper explores planetary detection, highlighting transit photometry and its powerful role in recent exoplanet detection in the cosmos. Transit photometry leverages the periodic dimming of a star's brightness that arises due to a celestial body orbiting in front of the star relative to the observer. One is then able to conclude whether or not a star hosts a planet. Transit photomoetry is a powerful method of detection that is capable of not just planetary detection, but also it is also capable of gauging the size of the exoplanet, finding its orbital period, and even inferring the atmosphere of the target via transmission spectroscopy. Its importance in astromomy is known, but particularly for this paper, transit photometry excels in showing its accessibiltiy and reliability. In this paper, we explore the tool of transit photometry and its application strictly in detection to see a successful detection of the exoplanet WASP-14b orbiting its host star WASP-14. WASP-14b is observed to cause a change of mangitude of 0.1 to its host star.

Keywords: Exoplanets — Transit Photometry — WASP-14b — GJ-1214b

1. INTRODUCTION

The first recorded cases of humans performing astronomy date back to the time of the Assryo-Babylonians, at around 1000 BCE. It was here, or maybe before, that humanity's curiosity peered far outside of the bounds of our solar system. The stars are an inseparable part of the celestial panorama that is our night sky. To better understand the cosmos, astrophysics and astronomy are at the forefront of studying the enigmatic nature of the sky. Exoplanet research represents a new branch in astronomy, and its primary focus is on the discovery and characterization of planets that are far beyond our solar system. Many methods are employed to find these new planets, but the one focused on this paper is transit photometry. Transit photometry's method of finding an exoplanet is to use a star's light, plotted against time, and determining whether or not a celestial body decreases the star's light intensity periodically via observation Lissauer (2017). Below, Fig. 1 is an artist rendition of transit photometry Ames (2022):

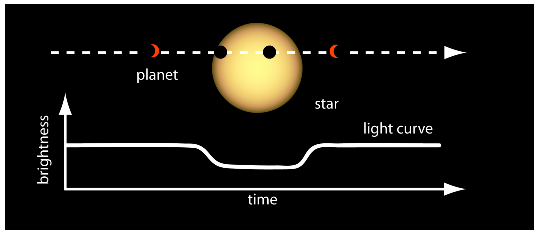

Figure 1. Depiction of planet occultation. The star exudes a constant light brightness, but once a planet's orbit interferes with the light of the star, the brightness dips, then after a period of time the transit ends and the brightness returns to its original value.

This initial detection detection paired with the characterization of the class of exoplanet, (that could be found with transit photometry as well as other methods) allows for a better understanding of solar system structures. Moreover, it allows for humanity to paint a more perfect picture of the night sky, ponder our place in the universe, and search for special planets that may be able to host life.

1.1. *Transit Photometry Method*

Delving deeper into the method of transit photometry, it depends on observing and analyzing the light flux emanating from a target star, with these readings contextualized against other celestial bodies within the same sky region. Collecting the data comprises of digital CCD (Charhed Couple Device) Earth-based cameras; this is just saying that the data may be collected on Earth with telescopes available. In the ideal transit experiment, the cameras capture the data of the target's star region during all stages—before, amidst, and post the transit. The captured images are subsequently transformed into a comprehensive flux dataset Afanasev (2018). For the data presented, that was done in python and the procedure will be explained in the methods section. Each image frame captured during the observation period corresponds to a specific flux value in a dataset, providing a time scale. A downside to this technique is that it depends heavily on the ability of the target to effectively block out the stars light.

1.2. *Differential Photometry*

Following the transit method, we use differential photometry to measure the apparent magnitude of the target stars and compare it to other standard stars in the neighboring region, in the same field of view. Good practice requires to observe these targets under the same conditions. Taking the difference between the the instrumental magnitude of the target and the instrumental magnitude of the standard, then adding the accepted magnitude of the standard star gives the apparent magnitude of the target. The technique offers for a way to calibrate the image and improve upon its accuracy by eliminating atmospheric error and equipment error. and this is essential as it is used to investigate the change over a time interval Kaur (2014).

1.3. *Aperture Photometry*

With the calibration complete, this is coupled with aperture photometry. Aperture Photometry represents a calibration technique which minimizes uncertainties within the aperture region of both the target star and its proximal comparison stars. The calibration process involves placing a circular patch (aperture) over the pixels that contain the target stars perimeter and a larger donut-shaped patch (annulus) extending beyond the target to capture the background sky light. With this, by subtracting the pixels in the annulus from the aperture, the background sky light (noise) can be eliminated. The aperture radius is set to half of the full width half maxima of the star's brightness curve and the annulus should be around twice the aperture to avoid accidentally including the starlight Kaur (2014). This setup aids in adjusting for any potential anomalies and variances within the specified aperture regions.

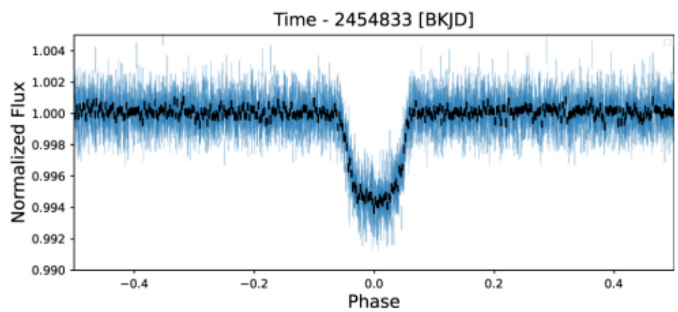

Figure 2. Here is a candidate exoplanet inferred from the host star Gaia EDR32077240046296834304 (G...304) this is a light curve typical in an academic article, it displays a time axis in the form of a phase-folded light curve plotted against the calibrated flux. A phase in transit photometry represents a specific point or period in the orbit of an exoplanet. Here, the phase of 0 represents the point where the exoplanet is directly between the observer and the host star. Phase folding is the process of aligning all observed orbits (data taken multiple times) onto one another. One important note about this figure is how subtle the change in intensity is from the normalized value to the transit value, it is less than one percent. Looking at the minima value, the change in intensity can be approximated to 0.6% Martínez-Palomera (2022)

.

Martinez-Palomera's data, depicted in Fig. 2, gives nominal behavior of a light curve that is transited by a celestial body. It shows the power of transit photometry, in how exoplanets may be inferred even with subtle changes in intensity. Astronomers are allowed to identify even the faintest of celestial companions utilizing powerful telescopes that observe the same stars (and more) that we see with the naked eye. It allows the continuing development of the universal portrait, creating a better understanding of what these solar systems outside of our own contain and a more complete picture. Perhaps more ambitiously, this method of detection (along with others) could potentially unveil a planet endowed with the necessary conditions to cradle the most complex of all - life.

2. EXOPLANET TARGETS

While conducting this experiment, the selection of the exoplanets were based off of Las Cumbres Observatory (LCO) Visibility Tool (LCO) and the NASA Exoplanet Watch Target List NASA (2023). From the LCO visibility tool, we were able to figure out what kind of targets were reasonable and the NASA Exoplanet Watch Target List provided planets that were observable during the month of April, May, and June of 2023 for all continents.

2.1. *Gliese 1214b*

GJ-1214b is a Neptune like exoplanet orbiting an M-type star, GJ-1214, which is near the same class as our sun which is a G2V class star Aeronautics & Administration (2023). It was discovered in December of 2009, as a part of the ground based MEarth project, which surveys the sky using robotic telescopes that focus on the observation of M-dwarf type stars in search of Earth-like exoplanets. With the mass detection method of radial velocity, the accepted value of the mass is 0.02571 M_J where "J" represents Jupiter. With the radial detection method of primary transit, the accepted value of the radius is 0.24463 R_J and an orbit of 1.58 days Exoplanet (2023).

Figure 3. Here is a raw image of GJ-1214 star captured on the LCO telescopes. It is the dot that is centered on the image and this was produced using DS9 which is an image display tool. Referring to aperture photometry, it seems to have a small contrast between the background and the target. This is not ideal because it means that there is a lot of noise.

The apparent magnitude of GJ-1214 is 14.71. The validity of making an observation using the available telescopes was first determined by noting the stars magnitude and then computing the "Signal to Noise Ratio" or "SNR". The SNR measures the target against its background where a high SNR is desired. The signal to noise ratio of an exoplanet orbiting a star is roughly:

$$(S/N)_{\text{Planet}} = T \cdot (S/N)_{\text{Star}} \tag{1}$$

Where the transit depth is

$$T = \frac{R^2_{planet}}{R^2_{star}} \tag{2}$$

The radius of GJ-1214 is $R_{star} = 0.216 R_{Sun}$ where R_{Sun} is the radius of the sun. Using the LCO SNR calculator along with first principles, the target GJ-1214b was found with an SNR of 77.4 $\sim$ (LCO).

2.2. *WASP 14b*

WASP-14b is a dense gas-giant exoplanet orbiting an F-type star, WASP-14 Joshi et al. (2009a) with an apparent magnitude of 9.75. Discovered in 2008 using Transit Photometry, it is observed to have a mass of 7.34 $M_{Jupiter}$ and a 2.24-day orbit. With the radial detection of primary transit, the accepted value of the radius for WASP-14b is 1.281 R_J and an orbit of 2.48 days Exoplanet (2023). The radius of WASP-14 is $1.306 R_{Sun}$ Exoplanet (2023). Using the LCO SNR calculator along with first principles, the target WASP-14b was found with an SNR of 102.4 $\sim$ (LCO).

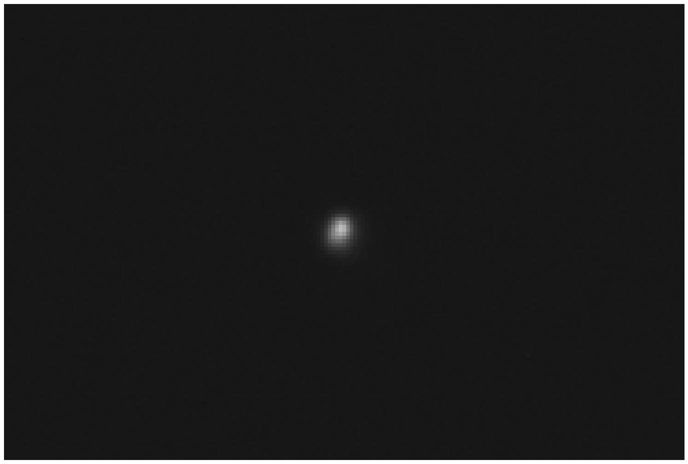

Figure 4. Here is a raw image of WASP 14 star captured on the LCO telescopes. It is the dot that is centered on the image and this was produced using DS9 which is an image display tool. One feature about this image compared to the raw image of GJ 1214 is that the contrast between the target and the background is high, making it easy to perform photometry.

The SNR difference between the two targets is large, why is that? For the target, GJ-1214b the target was selected primarily due to its application to transit photometry. It orbits a star similar to ours, which makes it an Earth-like candidate. WASP-14b on the other hand, does not, it orbits a star that exudes a much larger brightness and generally is a more massive candidate. The size of WASP-14b is a good example at exhibiting the strengths of transit photometry based on its size and the larger transit depth it can provide. A large transit depth will be able to compensate for the undesired potential oversaturation of a telescope collecting data.

3. METHODS

GJ-1214B

Now, for the observation of GJ-1214b, we used the 0.4 m telescope at the Los Cumbres Observatory on May 8, 2023: 12:30 am - 2:30 am UTC. The data set consists of 360 exposures with an integration time of 10 seconds. The settling time in between exposures was 14 seconds. The telescope used was the 0.4-meter telescope with an SDSS-i filter. This filter is ideal because it fall near the infrared spectrum. GJ-1214 b orbits an M-type star where it typically emits light orange/red light, with temperatures ranging from 2400 to 3700 K. Thus, it is best to use a filter sensitive to this range. To watch the sky, the telescope was set to the coordinates of a Right Ascension of 17:15:18.9 and a Declination of +04:57:50.06.

Target Name	RA (J2000)	Dec (J2000)	Filter	# Exposures	Integration Time (s)	Observational Windows
GJ-1214b	17:15:18.9	+04:57:50.06	SDSS-ip	360	10	May 8, 2023: 12:30 am - 2:30 am (UTC) (South America)

Observation Request 1: Observation Request for GJ-1214b

WASP-14B

For the observation of WASP-14b, we used the 0.4 m telescope at the Los Cumbres Observatory on May 17, 2023: 11:30 – 16:30 UTC. The data set consists of 360 exposures with an integration time of 10 seconds. There was the same amount of settling time in between exposures. This filter was the SDSS-g filter is ideal because WASP-14b orbits an F-class star, emitting yellow and white light, which is hot star with temperatures range from 6000 to 7500 K. The g-filter is sensitive to light from hot stars and radiation in the green spectrum. To watch the sky, the target was set to the coordinates of a Right Ascension of 14:33:06.0 and a Declination of +21:53:41.

Target Name	RA (J2000)	Dec (J2000)	Filter	# Exposures	Integration Time (s)	Observational Windows
WASP-14b	14:33:06.0	+21:53:41	SDSS-g	360	10	May 17, 2023: 11:30 am - 16:30 am (UTC) (North America)

Observation Request 2: Observation Request for WASP-14b

3.1. *Photometry*

With the telescope data collected, the general process of photometry on the images start with importing the astropy package on python which is able to import, read, and extract data in the form of .fits files from the telescope. Then, the Photutils package is used to detect sources in the images with the function ”photutils.detection” which helps in calibration by finding the sources to subtract. Additionally, the function ”photutils.aperture” is used to create the annulus and circular patch.

Now for the calibration, for an image find the number of stars and their positions. The banzai imagine is first displayed on a gray-scale color-map, where the image data is transformed with a logarithmic scale to see the changes of flux of the pixels. This will help python differentiate the stars from the sky. Due to the nature of the experiment, there are bound to be outliers and unwanted data, to deal with this the best way is to exclude the points that are 3 standard deviations away. This is done with the MeanBackground() function. Now, because the target is far away there may be some weaker sources, and the weaker sources may be found by utilizing the DAOStarFinder algorithm to better identify the stars in the image and determine their positions and brightness. To select appropriate star radius is to find the full width half maximum or ”FWHM” of the star otherwise known as its Gaussian sigma. The radius of the star aperture is half of the FWHM value, but it is good practice to set the star radius to five times the sigma radius. The radius of the larger background annulus should be set at least twice that of the inner annulus of the target. Below in Fig. 5 and Fig. 6, we see resulted star count for both GJ-1214b and WASP-14b.

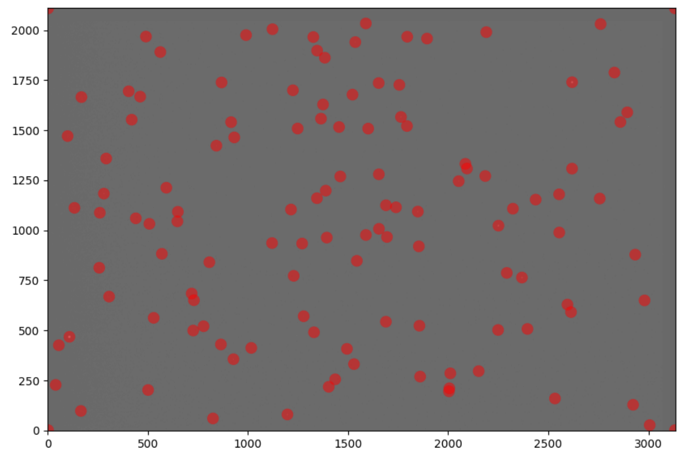

Figure 5. 117 sources were identified using the DAOStarFinder tool from Photoutils for GJ-1214b. Based on the quality of Fig. 3, the large data set and python code was able to compensate. As an additional check, the viewing software AstroArt was used to verify the relative location of some of the stars with respect to the target..

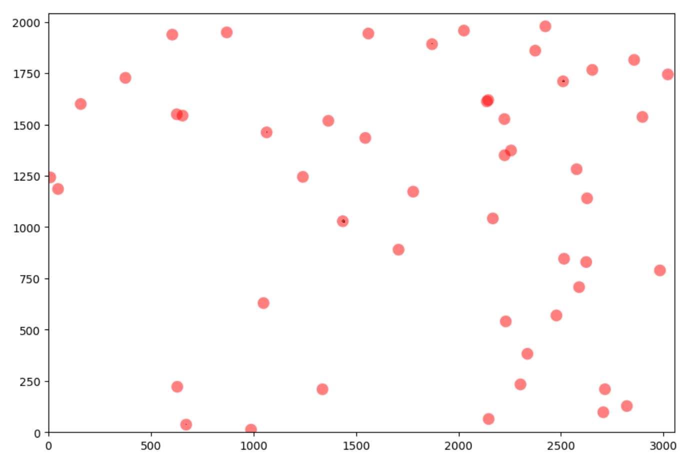

Figure 6. 50 sources were identified using the DAOStarFinder tool from Phototulis for WASP-14. This is surprisingly less than the result seen in Fig. 5 and a potential reason for this is that the star's magnitude is much larger, thus flusing out weaker stars. Again, an additional check was done with AstroArt to verify the relative location of some of the stars with respect to the target.

Now, move onto the larger set of data and finish the aperture photometry on the sources by inputting an inner annulus radius of enclosing the target. With the position of the target star defined, background data is analyzing with the "Background2D" function. The background data found from the function is taken away as aperture photometry is performed with the circular aperture tool. The radius was set to 15 pixels. Iterating over the exposures (frames), the brightness and positions are collected for all frames. Finally, a calibration function calibrates the median value of our target star's magnitude which is detailed in Fig. 7.

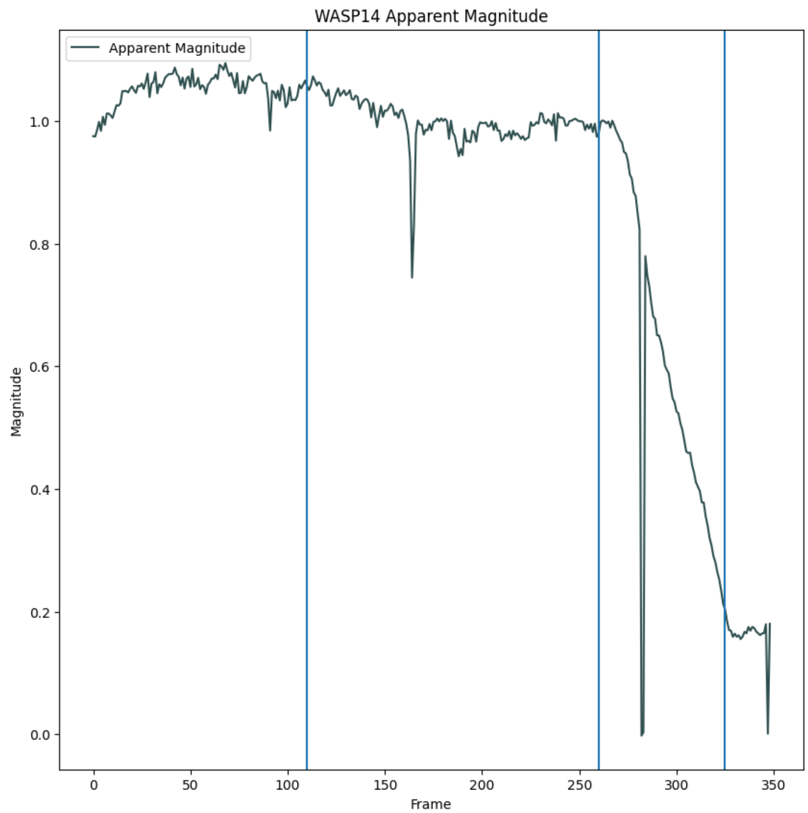

Figure 7. Here is a plot of the normalized calibrated magnitudes over each frame for WASP-14b. The horizontal blue lines show where the transit appears to start. The most left line shows an initial dip in magnitude corresponding to frame 110. The planet appears to begin its transit where frame 260 marks its start and frame 325 marks its complete planet occultation.

Now, the stars in the dataset are assigned weights based on their medium values. The stars are shown in the legend. A variability check is performed to identify then exclude calibrated stars that show significant variance in their weighted magnitudes. After filtering, a light curve is plotted showing the changes in intensity over the frames for the target along with the stars that passed the check. This is shown in Fig. 8 on the left.

Additionally, a different light curve is generated by plotting the variations in brightness of the target compared to the mean calibration curve. This allows for an empirical comparison of the behavior of the target and the calibrated stars. This is shown in Fig. 8 on the right.

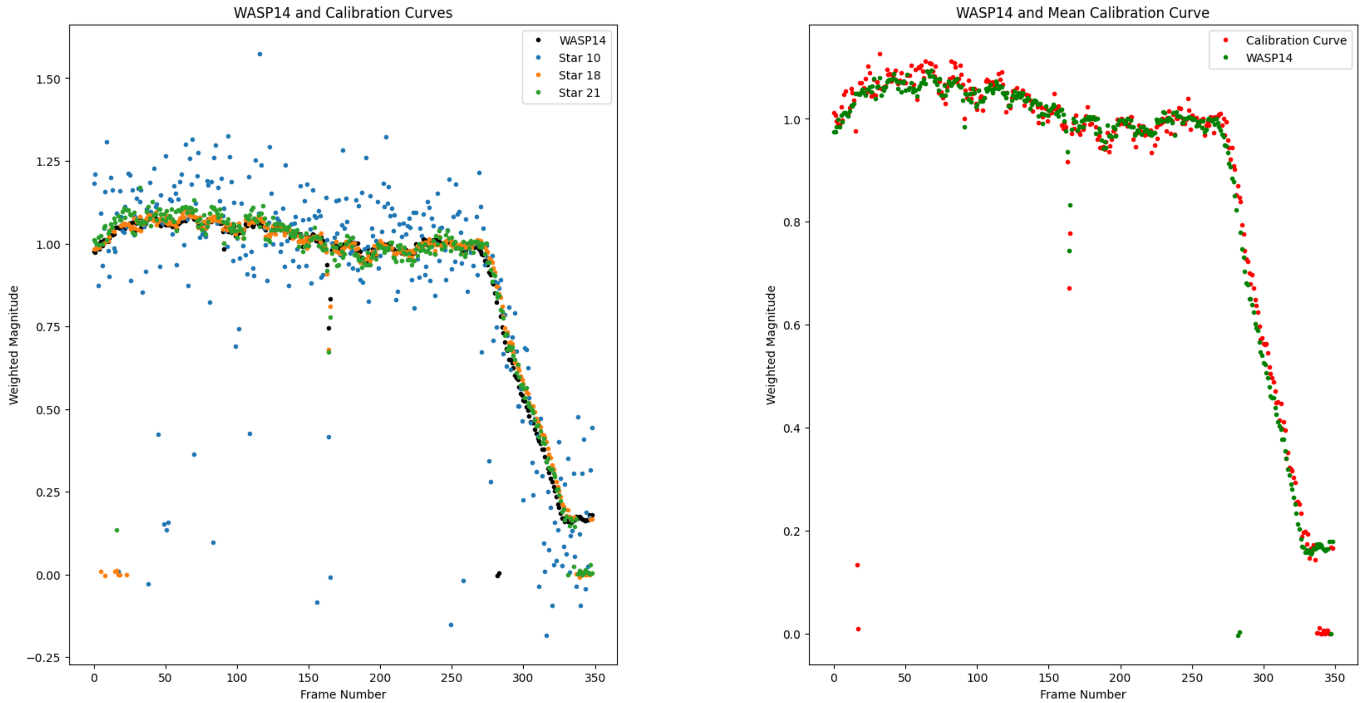

Figure 8. Here, Fig. 8a shows the result of plotting WASP 14b along with a few different stars. The weighting calibration is applied to these data sets to determine the magnitude and each measurement has a weight that tells its accuracy and precision. The weighted magnitude considers these weights and normalizes them to reduce error. Fig. 8b is similar, but here it plots WASP 14b against the calibrated weighted curve found by averaging the weights.

4. RESULTS

4.1. *GJ-1214b*

Results were inconclusive for GJ-1214b. The data was out of our skill-set to decode and thus no transit was detected.

ERROR ANALYSIS

To begin, a significant problem with the transit observation for this exoplanet was with the SNR ratio. GJ-1214b has a relatively good transit depth of about 1.5 percent Caceres (2014), but based on the LCO SNR calculation, it was not great. This can be attributed to both systematic error. The star needs to have an SNR ranging around 700 to be resolved and thus failed. Though M dwarves, GJ 1214, and hot Jupiters, GJ-1214b, are theoretically good targets, systematic error arose in that the equipment was not fit to capture the data. We had ensured that the filter was the ”i prime” filter was used, as that is the spectral range where M dwarves peak in brightness, but it did not work. The signal captured by the telescope was too faint. This limitation can be seen in Fig. 3 where the background noise relative to the target is close in data points.

4.2. *WASP-14 b*

Transits are best observed as square-like waves. Looking at Fig. 1 and Fig. 2, a square wave could best fit this type of function. Fig. 7 shows a good example of what the start of the transit looks like, as mentioned above, the star appears to dip its initial intensity at around frame 110 where the planet occultation occurs completely at frame 260 to frame 325. From frame 325, the light level remains relatively constant. Here is better visualization of the square-like behavior of WASP-14b's transit:

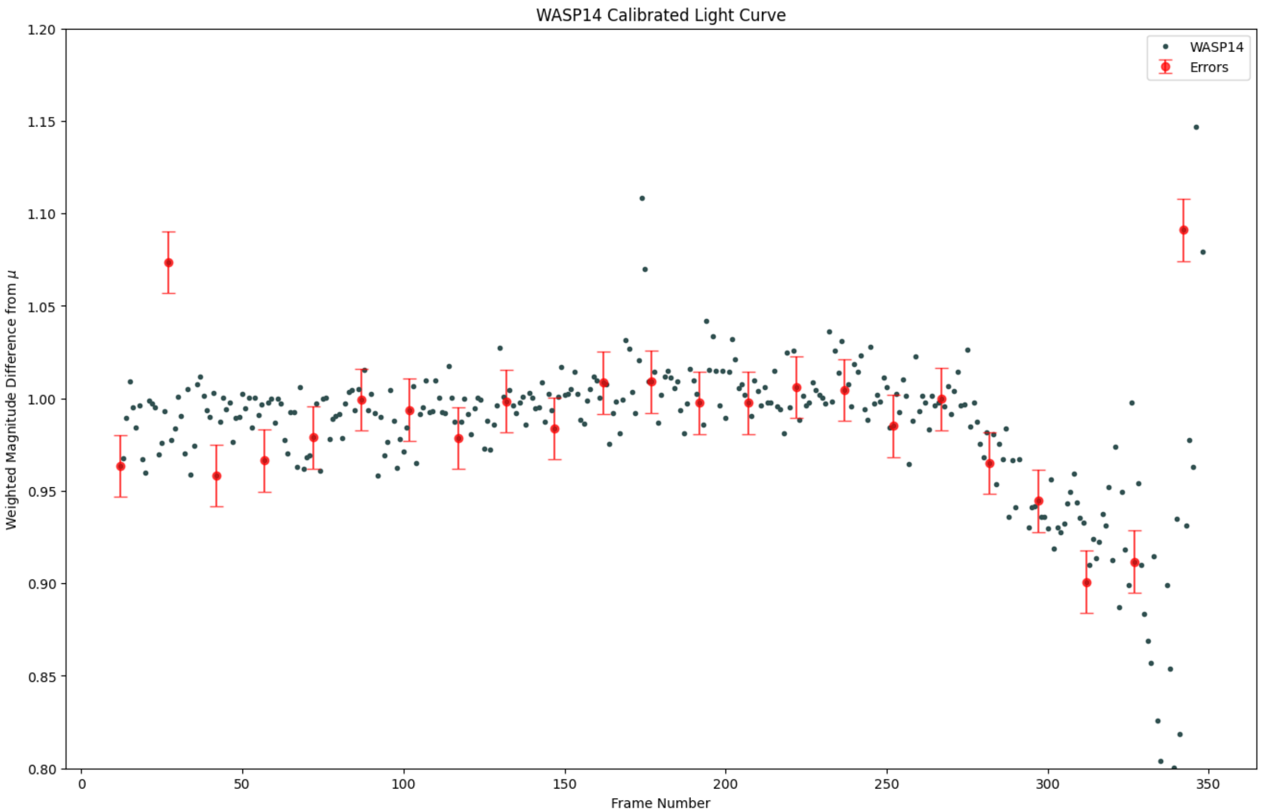

Figure 9. This shows the start of a successful transit. Though the data is cut off abruptly, there is a clear dip in magnitude.

Fig. 8b shows that there is a drop in the magnitude of the brightness of WASP 14 of about 0.8. Comparing this to literature, WASP 14b's dip in differential magnitude is around 0.01 Yoshi (2009). Fig. 9 cuts off at the start of the transit, but it seems like the drop in magnitude is 0.1.

4.3. *Error Analysis*

Briefly, there is a part of randomness where some significant outliers can be seen such as is systematic error which is visually seen as the random high magnitude spots in Fig. 9. These correspond to frame 35, 175, and 345 for example. There is an unpredictable data point at these frames.

Generally, the error comes in two parts, systematic and statistical. For the systematic error, this was corrected with the calibration as systematic behavior is predictable. Other than this, better equipment, telescopes, could be used in the future to get better resolution or selecting a smaller aperture could improve upon the data.

For the statistical error, this was done in python. The data was taken over 360 frames, so we decided to use error propagation to measure the statistical error. From the data, we took the standard deviation of WASP 14 before transit using static frames, a function in python, to find the points before transit. The magnitudes of these frames are stored into an array where the average is calculated. This is the mean for the statistical analysis. Here is what the code returned:

Table 1. Error Propagation

Results	
Mean $\equiv \overline{x}$	0.988987
Standard Deviation $\equiv \sigma$	0.01676
Variance $\equiv v$	0.0002811

Looking at these values, we should expect that the mean matches what is expected. A value of 0.988 for the average magnitude is reasonable for transit photometry. This implies that it deviates from 1 by 0.12 and a dip in magnitude by that value is sensible for transits. The standard deviation being small suggests less variable data points and thus a closely clustered data set. Likewise, the variance is small meaning the data is not spread poorly and rather it is close to the mean. This is expected behavior. Comparing this to other data, it is consistent in that it shows a transit that drops in magnitude ranging from 0.01 - 0.1 depending on the calibration.

5. DISCUSSION

The experiment showed that observing GJ-1214b was out of out skillset, the SNR was extremely poor which is one of the larger factors contributing to the error. Luckily, the transit of WASP-14b about WASP-14 was still observable and a successful light curve was presented that is sensible to current results in astronomy. We saw a dip in magnitude of 0.1. Though the data was cut short, compromising the signature square like wave, due to the wrong data set being downloaded, it is still viable in what it shows; a transit. Transit photometry is essential to completing the universal picture, and more hopefully to find planets that are capable of hosting life. With this project done, more steps can be taken to define more characteristics of the target such as the radius, orbit, and mass. Though we were limited by our tools and understanding, moving forward I believe we could perform another successful transit analysis. Finding a transit was the hardest part, understanding concepts like transit depth was essential to move forward with the successes of the project. If we had a better understanding, we would have avoided harder targets such as GJ-1214b, which still may have a viable data set, but is hard to filter through and analyze with photometry. Other than this, ensuring a high SNR as well as a high transit depth. This would ensure that no matter what equipment we use, we would see something. That is what saved the WASP-14b, it had the largest transit depth within the exoplanets visible from LCOs telescopes. Thanks to Jeongwha Kim, Sam Whitebook, and Dr. Lubin, we were able to use transit photometry to detect an exoplanet.

REFERENCES

Aeronautics, N., & Administration, S. 2017, Light Curves and What They Tell Us. https://avanderburg.github.io/tutorial/tutorial.html

—. 2023, GJ 1214 b. https://exoplanets.nasa.gov/exoplanet-catalog/6557/gj-1214-b/

Afanasev, D. 2018, Detection of Exoplanets Using the Transit Method. https://arxiv.org/abs/1803.05565

Ames, N. 2022, Light Curve of a Planet Transiting a Star. https://exoplanets.nasa.gov/resources/280/light-curve-of-a-planet-transiting-its-star/

Berta, Z. K., Charbonneau, D., Bean, J., et al. 2011, ApJ, 736, 12, doi: 10.1088/0004-637X/736/1/12

Caceres, C. 2014, Ground-based transit observations of the super-Earth GJ 1214 b. https://www.aanda.org/articles/aa/pdf/2014/05/aa21087-13.pdf

Charbonneau, D., Berta, Z. K., Irwin, J., et al. 2009, Nature, 462, 891, doi: 10.1038/nature08679

Exoplanet, E. 2023, Planetary Catalog. http://exoplanet.eu/

Henry, G. W., & Bean, J. L. 2023, arXiv e-prints, arXiv:2302.07874, doi: 10.48550/arXiv.2302.07874

Hood, C. E., Fortney, J. J., Line, M. R., et al. 2020, The Astronomical Journal, 160, 198, doi: 10.3847/1538-3881/abb46b

Joshi, Y. C., Pollacco, D., Cameron, A. C., et al. 2009a, Monthly Notices of the Royal Astronomical Society, 392, 1532, doi: 10.1111/j.1365-2966.2008.14178.x

—. 2009b, Monthly Notices of the Royal Astronomical Society, 392, 1532, doi: 10.1111/j.1365-2966.2008.14178.x

Kaur, K. P. 2014, Fundamentals of Differential and All-Sky Aperture Photometry Analysis for an Open Cluster. https://arxiv.org/pdf/2209.03015.pdf

(LCO), L. C. O. 2023, Visibility Tool. https://lco.global/observatory/tools/visibility/

Lissauer, J. J. 2017, Transit Photometry. https://www.britannica.com/science/transit-photometry

Martínez-Palomera, J. 2022, Kepler Bonus: Aperture Photometry Light Curves of EXBA Sources. https://iopscience.iop.org/article/10.3847/1538-3881/ac4331

Narita, N., Nagayama, T., Suenaga, T., et al. 2013, Publications of the Astronomical Society of Japan, 65, 27, doi: 10.1093/pasj/65.2.27

NASA. 2023, Exoplanet Watch. https://exoplanets.nasa.gov/exoplanet-watch/latest-targets/

Raetz, S., Maciejewski, G., Seeliger, M., et al. 2015, MNRAS, 451, 4139, doi: 10.1093/mnras/stv1219

Saha, S. 2023, Precise Transit Photometry Using TESS: Updated Physical Properties for 28 Exoplanets Around Bright Stars. https://arxiv.org/abs/2306.02951

Society, T. P. 2023, Down in Front!: The Transit Photometry Method. https://www.planetary.org/articles/down-in-front-the-transit-photometry-method

Vanderburg, A. 2020, Transit Light Curve Tutorial. https://imagine.gsfc.nasa.gov/features/yba/M31_velocity/lightcurve/lightcurve_more.html

Wong, I., Knutson, H. A., Lewis, N. K., et al. 2015, The Astrophysical Journal, 811, 122, doi: 10.1088/0004-637X/811/2/122

Yoshi, Y. C. 2009, WASP-14b: 7.3 M J transiting planet in an eccentric orbit. https://academic.oup.com/mnras/article/392/4/1532/965181