The Detection of Sundialia - Confirming the Existence of an Exoplanet

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Introduction

In our project, we utilized data from NASA's Transiting Exoplanet Survey Satellite (TESS) in an attempt to discover an exoplanet. Designed to observe variations in light coming from thousands of objects in our galaxy[2], TESS provided us with potential planet candidates through a series of data reports. Using these reports, we compiled a list of candidates which fit a set criteria, and with the Leuschner Observatory[3], we observed said candidates. Through this, we attempted to confirm the existence of our monitored exoplanet.

An exoplanet is a planet that orbits around a star outside our solar system. Since exoplanets are so far away from us - billions of times less bright than the stars they orbit - they are incredibly hard to see. To overcome this limitation, we used the Transit Method, which measures the amount of light from a star that reaches us over a period of time[4]. If there is a planet that orbits said star, the amount of light we measure slightly lowers. Regarding the dip in light as a result of the transit, we have to ensure that the dimming is due to an actual transit, as it could otherwise be the result of some other object, noise, or instrumental issue. A too-rapid or large dip could indicate a binary star or noise, and one that isn't periodic would not be a planet.

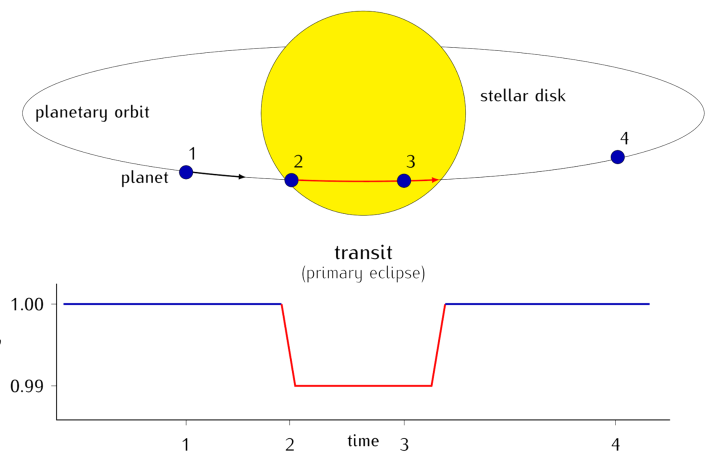

Figure 1. Depiction of Exoplanet Transit[5]

Methodology - Choosing a Candidate

To begin our project, we first referenced several reports from TESS, which showed the data of several transiting bodies (Figure 1). In doing so, it was crucial that the reports we considered to be 'candidates' were actually observable exoplanets, since many of the filed reports included celestial bodies that were not planets, or weren't observable due to our position on Earth and the technological limitations of the Leuschner Telescope. Firstly, our candidate needed to be large enough to block a noticeable amount of its host star's light, so the radius ratio of planet to star (R_p/R_{star}) needed to be around 0.1 (Figure 2). Anything below this threshold was too small to be observed by the telescope, and anything above was likely a binary star system. We also needed an occultation below 5.0 $\sigma$to ensure there was no secondary eclipse, which would be indicative of a binary star. Additionally, this relative flux graph needed to appear relatively U-shaped, as this accurately depicts the smooth transit of an orbiting exoplanet (besides limb darkening). To meet our telescope's physical limitations and ensure that our star was observable in the Berkeley night sky, our star's right ascension and declination needed to lie between 8-12 hours and 5-70 degrees, respectively. In finalizing our candidates, it was preferable that our planet orbited its star several times a month (P) (Figure 2) and had a transit duration of approximately 2-4 hours (T) (Figure 2). This allowed us to consistently observe and account for any delays due to weather. After finalizing a list of potential candidates, we used the T_0 value given in the reports to calculate the exact time and date of the transits and contacted Professor Alan Chew to supervise the remote use of the Leuschner telescope.

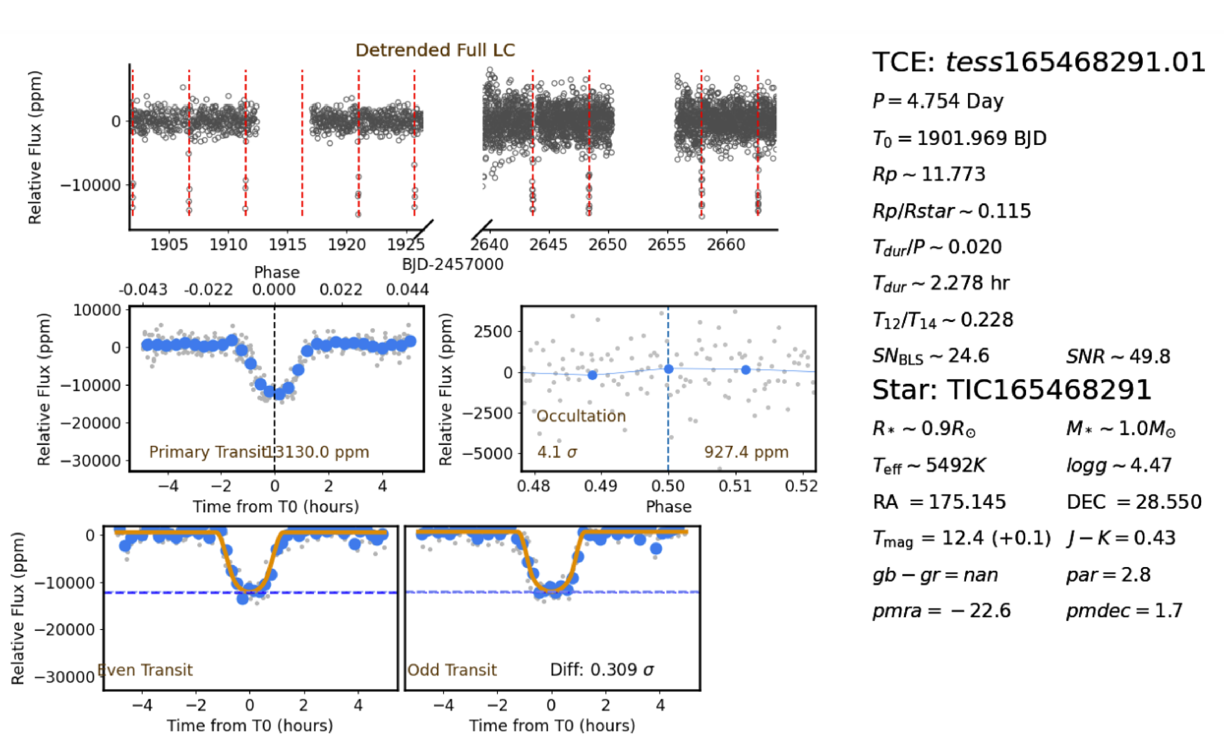

Figure 2. TESS Report[1]

Methodology - Observation and Analysis

Once we had chosen our exoplanet candidate, the next step was to start observing its transit. Prior to observing, we made sure to check that our transit parameters, such as transit depth, duration, and timing, were optimal.

First, we located our planet at an RA of 11:40:34 hours and DEC of 28.550° to set up the telescope. Then, we focused Leuschner to approximately 25,800 micrometers after applying the G-band filter. This setup allowed us to see our star clearly and other stars we could use as references. We checked our star's brightness against these references and watched for any movements while observing. During the transit, we used Leushner's camera to capture images every 120 seconds to gather data. Using Python's NumPy, Matplotlib, and Scipy packages, we calibrated each image using dark and flat frames, then selected the region of interest containing our exoplanet and its host star. We measured the flux of the star and the exoplanet while selecting two reference stars for relative flux comparison. This comparison helped ensure that any flux changes were due to the transit, not external factors like light from the Moon or variability in the star. We then converted flux measurements into normalized light curves, reducing noise in the data. Comparing the flux from our target to that of two separate reference stars allowed us to remove artifacts and reveal a transit-like curve. Finally, using the model's transit parameters, we determined the exoplanet's physical properties, such as its radius and distance from the host star.

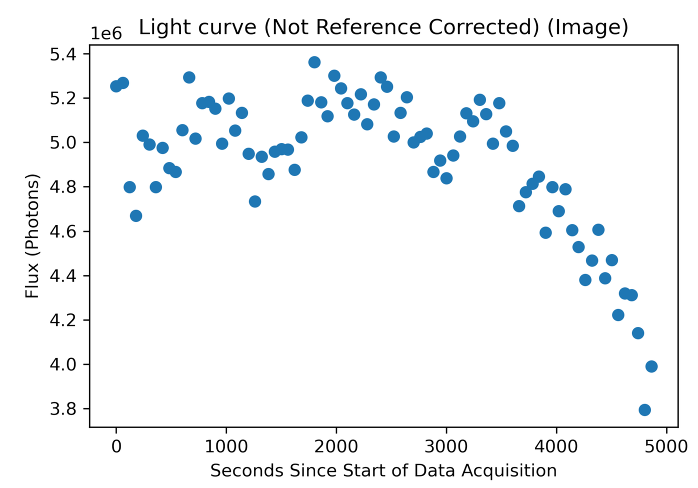

Figure 3. Light Curve of Science Star (Not Reduced)

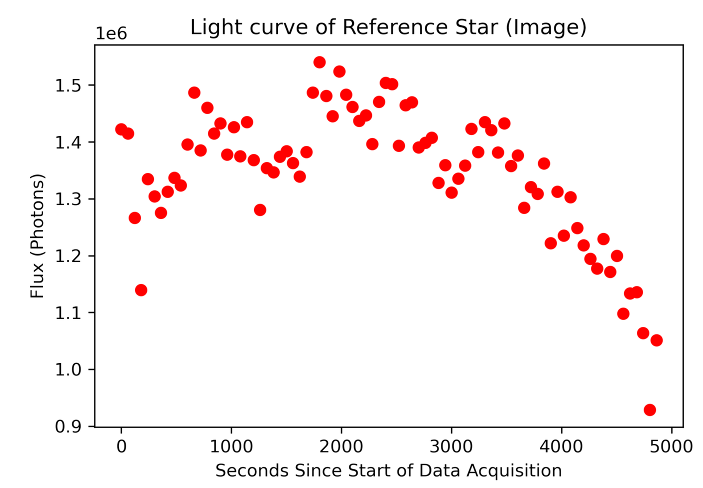

Figure 4. Light Curve of Reference Star (Not Reduced)

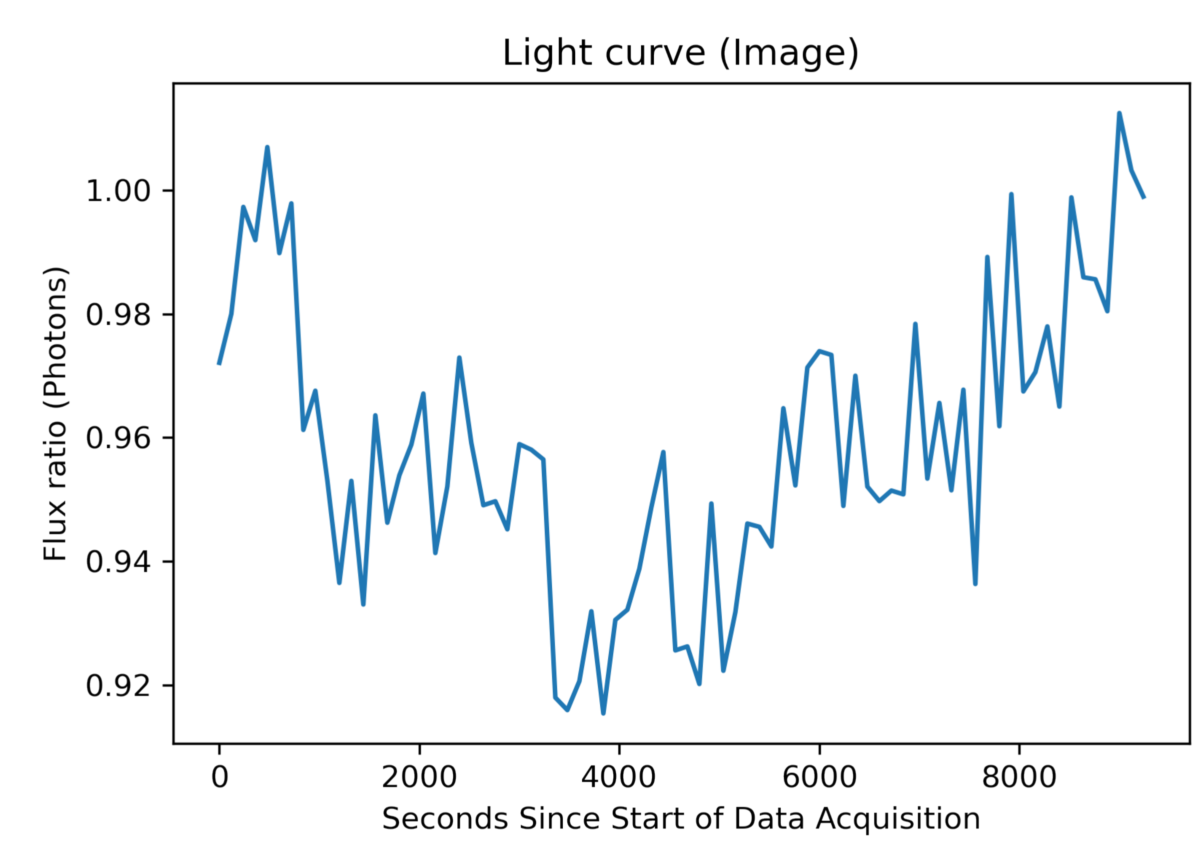

Figure 5. Reduced Light Curve of Science Star

Data Analysis/Machine Learning

In our analysis of TESS reports, we applied machine learning techniques to TESS's database to assist us in finding potential candidates. We did this by initial data preprocessing with Pandas and a Random Forest Classifier, allowing us to efficiently filter out reports from our RA and DEC range for our limitations with the Leuschner Telescope. Once we had the TESS reports in our range, we individually analyzed each one, looking for our optimal conditions. We chose this method as its resistance to overfitting made much more accurate in identifying potential exoplanet candidates amidst many false positives. We were able to quickly and easily narrow our search from thousands of reports to just a few dozen. This significantly cut down on the time spent researching for optimal objects and allowed us to spend more time observing and analyzing incoming data.

Data

The images and model showcase relative flux per time, known as a light curve. Based on these light curves, we can measure that the host star from Earth during the exoplanet transit had around 1.6% of the relative flux, which was within the boundaries of our expected transit dip and was more characteristic of an exoplanet than a binary star. Examining the transit depth, we found that the data captured from the Leuschner telescope relatively matches the TESS data provided as they had a transit dip of 1.3%. The planet's radius was found to be ∼12 Earth radii. The density of our planet was 0.802 g/cm³, which allows us to assume that our planet would be gassier and less dense than Jupiter which has a density of 1.33 g/cm³. We calculated the habitable zone, the area where an exoplanet is close and far away enough from the host star to have liquid water, to be found at approximately ∼0.77-1.11 AU using the TESS data given and calculating the value (along with additional parameters) based on the following functions:

$$r_i = \sqrt{\frac{L_{star}}{1.1}}\ ,\ r_o = \sqrt{\frac{L_{star}}{0.53}}$$

$$\delta = \left(\frac{R_P}{R_*}\right)^2,\ T_0 \equiv \frac{R_* P}{\pi a},\ T \approx T_0\sqrt{1-b^2},\ \tau \approx \frac{T_0}{\sqrt{1-b^2}}\frac{R_P}{R_*}$$

Figure 6. Exoplanet Transit Functions

The left radius was the inner radius of the habitable zone, and the right was the outer radius. The planet's semi-major axis was found to be approximately 0.083 AU, meaning it was about twelve times closer to its host star than Earth is to the Sun. With our habitable zone extending from 0.77-1.11 AU, we confidently determined our planet was not in the habitable zone.[4]

Conclusion

Using the Leuschner Telescope, we were able to state that the object we observed is likely a Hot Jupiter planet, orbiting quickly around its host star. As a group, we unofficially named this exoplanet "Sundialia." Considering the distance from its host star is 0.083 AU, it is unlikely that our planet is able to support life, as the intense heat and the constant barrage of stellar ejecta likely renders this gas giant a hot, barren world. The calculated radius of the planet from our data was found to be ∼12.4$R_\odot$, which nearly matched the 11.7$R_\odot$ found in TESS data. Our transit depth of 1.6% also nearly matched the 1.3% dip seen in the TESS data. This data increases the certainty that this object can be classified as an exoplanet orbiting its host star.

Future Work

Due to the poor weather conditions in the spring semester, we were only able to monitor a few transits for our potential candidates. In the future, we hope to observe at least three full transits to lower our errors and help officially confirm the exoplanet by TESS's follow-up standards. In addition to more observation opportunities, in the future, we hope to have more time to analyze our light curve data and create a strong case to confirm the exoplanet. Due to the quick turnaround time between our observation and the end of ULAB, we could roughly confirm the planet type using our data.

Acknowledgements

We would like to send a heartfelt thank you to Professor Alan Chew for generously donating his time and expertise to our project. He not only taught all of us how to use the Leuschner telescope, but he also helped set up countless viewing appointments and served as an outlet of knowledge during our eventual transit observation. In addition, we would like to thank the ULAB staff – Directors Rav Kaur, Anmol Desai, Saahit Mogan, Lab Manager Jordan Duan, and Faculty Advisor Dan Kasen - for providing us with this pivotal research opportunity. We could not have done this without all of you!

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