A Rainy Discovery - Confirming the Existence of Exoplanet Pluvia

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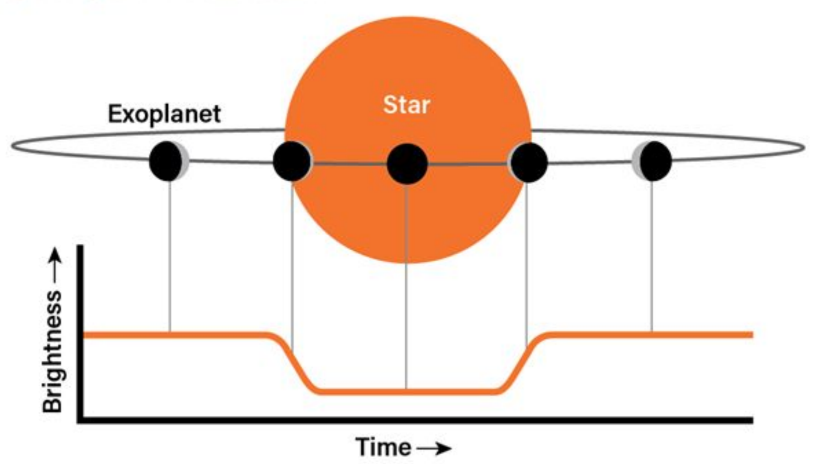
Introduction

For this project, we utilized the Transit Method in locating and confirming an exoplanet. This was done through the use of NASA's Transiting Exoplanet Survey Satellite (TESS), a telescope designed to search for exoplanets, which provided us with reports of potential planet candidates.[2] Using these reports, we predicted the transits of the best candidates and employed the use of the Leuschner telescope to officially monitor the predicted transit of the most promising candidate. Through this process, we were able to confirm the existence of our monitored exoplanet!

To successfully understand our project, it is important to understand the terminology. To begin, an exoplanet is a planet that orbits around a star other than our sun. Since exoplanets are so far away from us, are small compared to their star, and don't emit their own light as stars do, so direct imaging is impractical in most cases. To work around this limitation, there are two main methods of planet detection: the Radial Velocity Method and the Transit Method. We used the Transit Method, which is when one measures the amount of light from a star that reaches us as an object 'transits,' or moves, in front of it compared to multiple close-by reference stars. In regarding the dip in light as a result of the transit, we have to make sure 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 gas cloud, and one that isn't periodic would not be a planet.

Figure 1:
Depiction of Exoplanet Transit



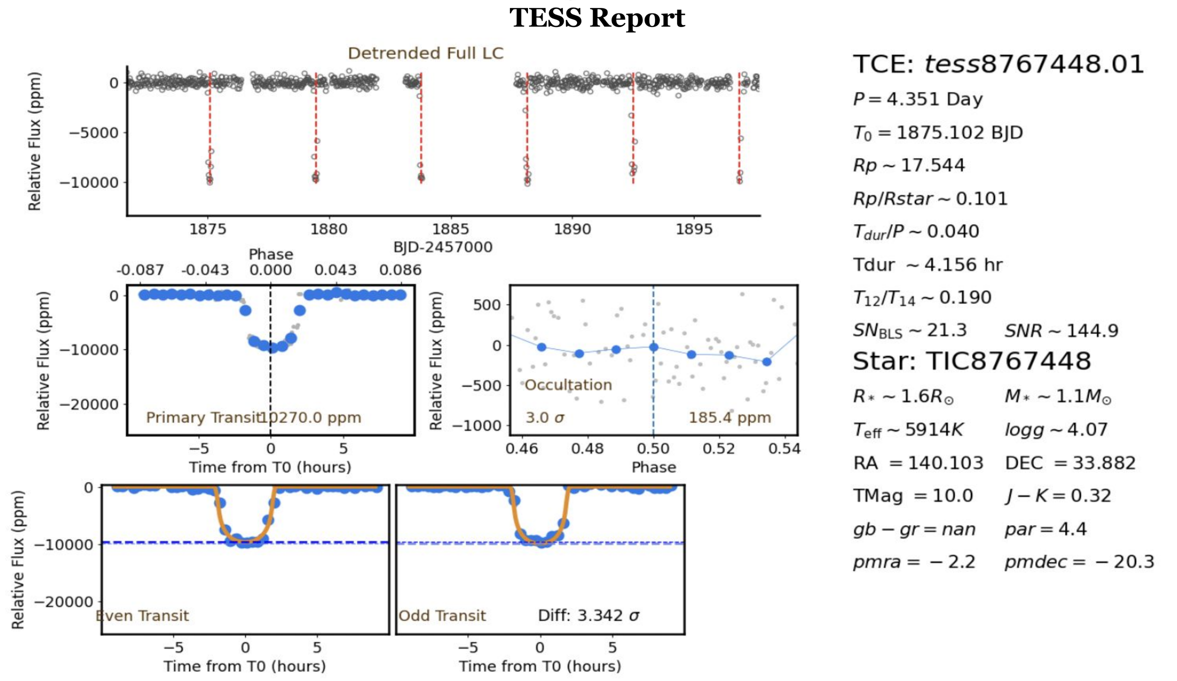
Methodology - Choosing a Candidate

To begin our project, we referenced data reports from TESS, which showed transiting bodies monitored by the satellite[1]. It was very important to choose a candidate that was an observable exoplanet, as many of the reports described bodies that were (a) not planets, or (b) not observable due to various reasons, such as our position on Earth and the limitations of the Leuschner telescope. In searching for the perfect contender, we had to consider many different factors. To begin, the radius of the planet, as well as the radius ratio between the planet and the star, was vital because we needed to make sure our planet was large enough to block a detectable amount of light, but not too large to be a sign of a binary star. The primary transit works similarly: a primary transit below 10,000 ppm meant that the potential planet was likely too small to be monitored, and a primary transit above 20,000 ppm meant the object was probably not a planet at all, but instead a binary star.

Qualitatively, we searched for reports with U-shaped curves, as this indicated a smooth transit characteristic of a planet. A desirable occultation sigma (both even and odd) was one below 5.0, as that indicated an object with a stable orbit that was not characteristic of a variable star. The declination and right ascension values needed to lie between 0 and 70, and 130 to 200, respectively, to guarantee that the planet was observable in the Bay Area night sky during the spring semester. Lastly, we considered the period of the planet and duration of transit. A planet that orbited several times a month, and orbited at night, was necessary as it meant we would have several chances to monitor it. A transit of 2-4 hours was preferable as it was long enough to observe a solid curve, but not so long that the full transit was not able to be detected in a single viewing.

After sifting through thousands of TESS reports, we came up with several candidates that met the desired criteria. We then used the T_0 given in the report to calculate the exact transits timings, and then reached out to Professor Gaspard to inquire about the availability of the Leuschner telescope so we could view our candidate.

Figure 2:
TESS Report



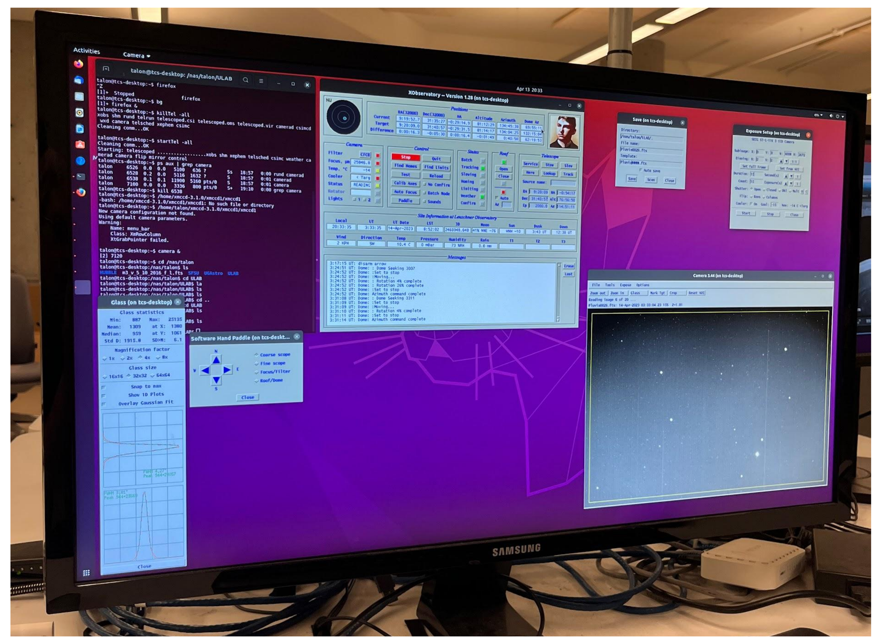


Figure 3:
Image of Leuschner Telescope Observation program

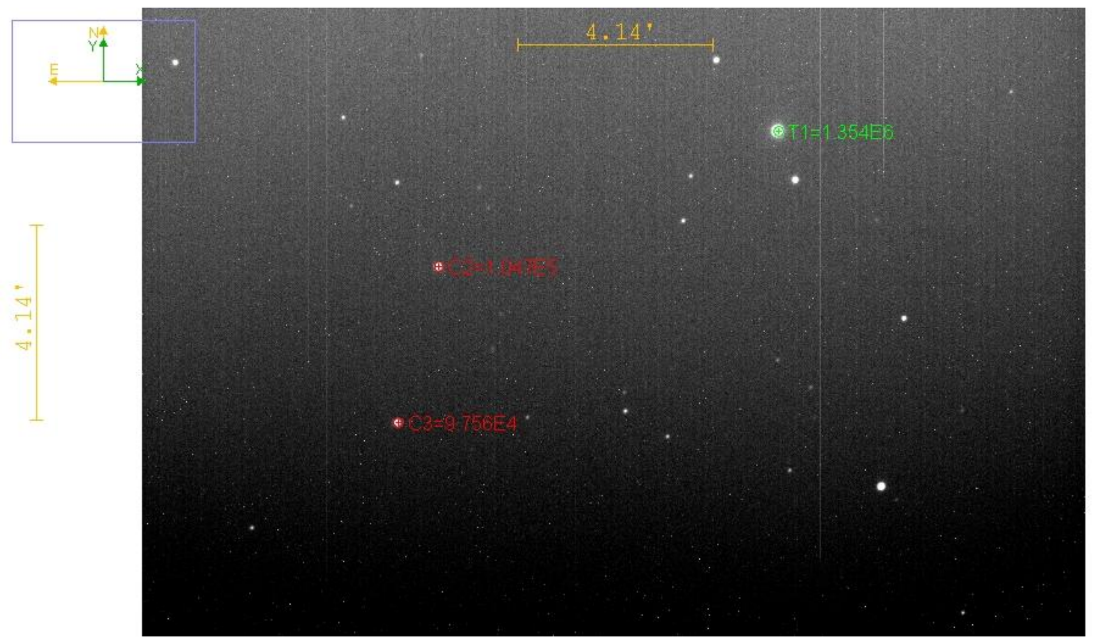


Figure 4:
Capture of exoplanet star and reference stars

Methodology - Observation and Analysis

After choosing our exoplanet candidate and getting telescope time for our proposed planet, the next step was to officially observe the transit. We made sure we were clear on our transit parameters beforehand, such as the transit depth, duration, and timing, allowing us to set up according to them before the transit.

To set up the telescope we first found our planet at an RA of 9:20:09 and DEC of 33.882°. Then we applied the V-band filter and focused Leuschner to roughly 25,800 micrometers. This set up gave us a clear view of our star, as well as reference stars. We used these reference stars to compare our light curve against after viewing, as well as track movement throughout the viewing to ensure our star remained in frame.

To actually capture our data we used the camera on Leuschner to continuously take fifteen second exposures for the duration of our transit. From these exposures we were able to obtain numerical data on the flux of our target throughout the source of our transit. It is worth noting that we were not able to observe the entirety of the transit due to the humidity percentage reaching a dangerous level. Therefore, our data and photos do not show the entirety of the end of the transit.

To analyze the images and obtain the flux information we utilized AstroImageJ, a software designed specifically to process telescope images. We opened each image in AstroImageJ and calibrated it using the calibration frames, which included dark and flat frames. We then selected the region of interest (ROI) in the image that contained the exoplanet and its host star. Using the aperture photometry tool, we measured the flux of the star and the exoplanet in the ROI while also picking two reference stars to get relative flux. The relative flux was important because we needed to be sure that the transit dip due to our planet was not some outside error such as dust or our target being a variable star. If our target showed a dip in flux due to a transit compared to the reference stars, that would tell us that our planet did exist as believed.

Analyzing our data began with using the light curve tool on AstroImageJ to plot relative flux over time. We then used Python to convert the flux measurements into normalized light curves. This was performed through the use of numpy, matplotlib, and a scipy package that bins flux measurements to clean up the noise in our data. We compared the flux from our target to two separate reference stars, then compared to both reference stars at once to remove artifacts and uncover a transit-like curve. From these graphs, we were able to use the transit parameters obtained from the model to determine the physical properties of the exoplanet, such as the radius of the planet and the distance from its host star.

Figure 5:
Normalized Light Curve Comparisons

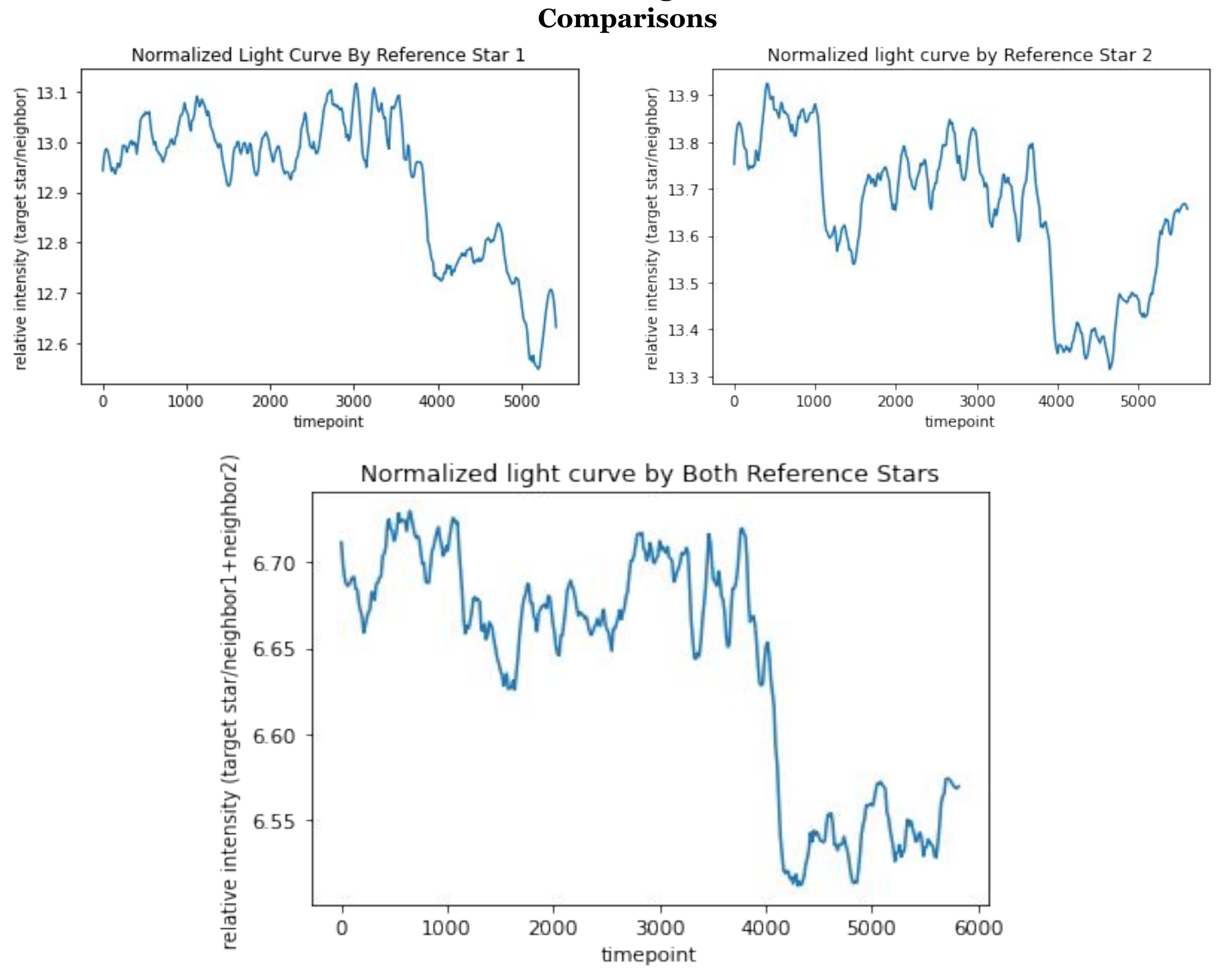
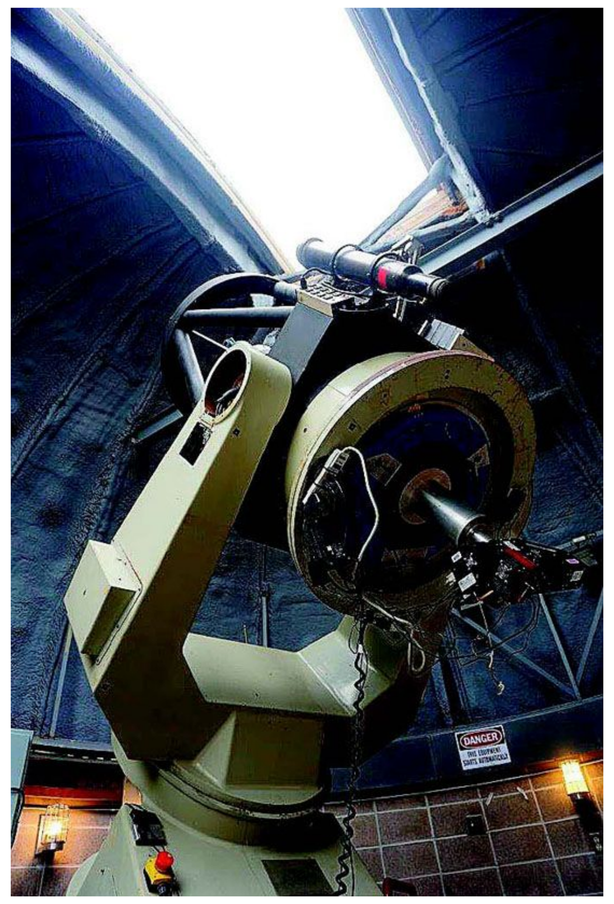


Figure 6: Leuschner Telescope[3]



Data

The images and model provided a relative flux per time curve. The normalized data, using only one reference star in the top right of Figure 5 and the top left of Figure 5 provided a percent change in flux of ~1.32% (albeit carrying some artifacts from the reference stars used). This could be seen in the top left of Figure 5 during the pre-transit and in the top right of Figure 5 during the post-transit. This was accounted after reviewing the normalization via both reference stars present in the bottom of Figure 5, which shows a percentage change of ~1.32%. This percentage of the relative flux was within the boundaries of our expected transit dip, and was more characteristic of an exoplanet than a binary star. This data additionally agrees with and backs up the relative flux percentage change found in the TESS light curve of ~1%.

Examining the transit depth we found that the data captured from the Leuschner telescope relatively matches with the TESS data provided. The planet radius was found to be ~20 Earth radii. 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 ~1.6-2.3 AU using the TESS data given and calculating the value (along with additional parameters) based in the follow functions:

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

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

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 ~0.1 AU, meaning it was about ten times closer to its host star than Earth is. With our habitable zone extending from 1.6-2.3 AU, we confidently determined our planet was not in the habitable zone.[4]

Conclusion

Using the Leuschner Telescope we were able to confidently say that the object we observed was a Hot Jupiter planet, an exoplanet that is big like the planet Jupiter while being close enough to have an immense amount of heat. Considering the distance from its host star being 0.1 AU, Pluvia was very unlikely to be habitable, as the intense heat from its host star, along with the constant barrage of stellar ejecta likely rendered this gas giant a hot, inhospitable world.

Our transit depth of 1.32% nearly matched the ~1% dip found in the TESS data. Our calculated radius of the planet was found to be ~20.1R⊕ which nearly matched the 17.5R⊕ found in TESS data. Our calculated orbital inclination of the transit was found to be ~88.7 which would be a near edge on orbit that would be expected from a TESS object, confirming the legitimacy of our observations in terms of inclination. This data increases the certainty that the scientific community can have to classify this object 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 single transit for Pluvia. In this transit, we were forced to stop early in the transit due to the humidity, making the weather our greatest enemy during this project. In the future, we would hope to observe at least three full transits to lower our errors and officially confirm the exoplanet by TESS's exoplanet follow-up standards to register Pluvia as an exoplanet.

In addition to more observation opportunities, in the future we hope for more time to analyze our light curve data. Due to the quick turnaround time between our observation and the end of ULAB, we unfortunately were only able to compare our target star to two reference stars, rather than our preferred three.

References

1. "TESS Project Pipeline." Data, MIT, tev.mit.edu
2. "TESS Exoplanet Mission." NASA, NASA, 24 August, 2021, https://www.nasa.gov/content/about-tess.
3. "Leuschner Observatory." UC Berkeley Department of Astronomy,
4. Dressing, Courtney. "Introduction to Astrophysics Lecture 11: Exoplanets Part One." 5, October, 2021

Acknowledgements

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