Draft version September 5, 2024
Typeset using LaTeX **twocolumn** style in AASTeX631

Ground-based Observations of TESS Object of Interest TOI-3521.01 for Light Curve Follow-up Validation

Nairi Davidian[1] and Peter Plavchan[2]

[1] *Watertown High School*
Watertown, MA 02472, USA
[2] *Department of Physics and Astronomy*
4400 University Drive MS 3F3, George Mason University
Fairfax, VA 22030, USA

ABSTRACT

This investigation aims to further confirm, characterize, and classify the Transiting Exoplanet Survey Satellite (TESS) Object of Interest (TOI) 3521.01 as a false positive or a valid exoplanet. Verifying the candidate is necessary due to sources of false positives, such as eclipsing binaries, sometimes posing as exoplanet candidates. To achieve this, we created a light curve by analyzing ground-based observations from George Mason University (GMU) in AstroImageJ (AIJ). The consistency of the light curve with the predicted ingress time, egress time, and depth suggests that the detection of TOI-3521.01 by the TESS mission is accurate. If it is a genuine exoplanet, it appears to be a hot Jupiter orbiting a star similar to our Sun. However, because we could not rule out the possibility that the detection was an eclipsing binary acting as a false positive, the results of this validation were ultimately inconclusive. After we confirm that TOI-3521.01 is an exoplanet, we should obtain the planet's mass through Doppler spectroscopy to confirm its status as a hot Jupiter.

1. INTRODUCTION

Since the dawn of human history, we have been captivated by what lies beyond our planet. Until a few decades ago, we had no confirmed evidence of planets beyond our solar system. Now, exoplanet astronomy has come to the forefront of modern science. While there are many different methods for detecting exoplanets, such as Doppler spectroscopy, direct imaging, microlensing, and pulsar timing, transit photometry is one of the most popular methods. The prominence of transit photometry is in part because of the repetitive nature of transits. An exoplanet orbiting its star will eclipse it on each period of its orbit. Therefore, we can observe the same exoplanet transiting its host star multiple times, which allows us to verify the candidate using the same method.

The Transiting Exoplanet Survey Satellite (TESS) is a space-based observatory designed to be most sensitive to Super-Earths orbiting nearby bright stars. It observes each 24-degree by 90-degree strip of the sky for 27 days and nights using four identical cameras in tandem(8). As done in this study, researchers use ground-based photometric observations to validate candidates identified by the TESS mission. This procedure is critical to the TESS Mission because deep images of exoplanet candidates and spectra of their host stars assist the TESS team in discerning which of these candidates are most likely to be genuine exoplanets. The TESS team then obtains the minimum masses of the approved candidates using Doppler spectroscopy, which detects shifts in the radial velocity of the host star. With access to each planet's minimum mass and estimated radius, the latter of which is determined using the transit method, scientists can use the predicted densities of these planets to infer their compositions (9).

TESS has already provided ample exoplanet candidates to examine using ground-based observations. Consequently, there is an abundance of work that researchers have done using transit photometry that accomplishes various goals. For instance, "Spinning up a Daze: TESS Uncovers a Hot Jupiter orbiting the Rapid-Rotator TOI-778" (1) details the discovery of a hot Jupiter that orbits a rapidly rotating star. The methods include utilizing light curves obtained from ground-based photometry in addition to radial velocity measurements. This discovery was especially exciting, given that most exoplanets discovered by TESS orbit stars that rotate slowly. Similarly, "Another Shipment of Six Short-Period Giant Planets from TESS" (7) discovers and characterizes six transiting hot Jupiters using transit photometry and radial velocity measurements. The scientists who produced this paper also found that these planets all orbited bright host stars. These discoveries show how apt TESS is to aid in discovering and characterizing giant planets with a shallow orbit. This trend makes sense because a transit in this system would provide the most apparent change in flux from that star.

Of the 7,208 exoplanet candidates TESS verified, 542 have been confirmed so far (6), which indicates that there is still an abundance of available data that we need to analyze to determine whether more candidates are genuine exoplanets or false positives. The most common sources of false positives are eclipsing binaries, star systems in which two stars orbit their center of mass. When one star eclipses the other, it can be mistaken as an exoplanet transit because both events involve a drop in flux of the perceived host star. Therefore, it is essential to examine each candidate closely and perform precise statistical analysis to determine whether or not it is a false positive. Once this possibility is ruled out, information obtained from the light curve can reveal characteristics of the planet for further investigation. In particular, the ratio of the change in flux of the star caused by the transit to its total flux is equivalent to the square of the ratio of the planet's radius to the star's radius, as shown in Figure 1. Knowing the planet's radius can provide clues as to what type of planet the candidate may be. When the planet's mass is also known, we can calculate its density, giving insight into its composition, which is one of the distinguishing characteristics in the search for Earth-like planets. Although others have performed follow-up observations of TOI-3521.01, no one has yet dedicated a paper to TOI-3521.01, indicating the need for an interpretation of follow-up observations to construct conclusions about the candidate.

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$$

Figure 1. Relationship Between Stellar Flux, Change in Flux Due to Transit, Stellar Radius, and Planetary Radius

This paper presents follow-up observations of TOI-3521.01 to investigate whether or not its transit occurs on the expected star at the expected time with the expected duration and depth provided by TESS. Section 2 discusses information about TOI-3521.01 and its host star known prior to our study, as well as our ground-based observations of TOI-3521.01. In Section 3, we detail our analysis of our data using multi-aperture photometry and the creation of a light curve via AIJ. In Section 4, we present the results of our study through figures of our light curve and nearby eclipsing binary (NEB) check. Section 5 discusses our conclusions about TOI-3521.01 based on the fit of our transit model to our data and our NEB check. As well as discussing the likelihood of TOI-3521.01 being a genuine exoplanet, we explore its possible characteristics. Section 6 summarizes our findings about TOI-3521.01 and presents and propositions for further work.

2. OBSERVATIONS

In section 2.1, we present the stellar and planetary parameters of the TOI-3521 system, as found on NASA Exoplanet Archive (10) and the Exoplanet Follow-up Observing Program (ExoFOP) (3). We also present the light curve obtained from the TESS data itself. In Section 2.2, we present a speckle sensitivity curve submitted to ExoFOP. Meanwhile, Section 2.3 details the processes used to obtain raw science images of our target at GMU.

2.1.

Here, we present parameters of the host star of TOI-3521.01 (10) and the light curve obtained from TESS data.

Distance (pc)	3357.22
T_{eff} (K)	5757.3
Right Ascension (RA)	21:07:45.54
Declination (DEC)	+31:46:51.42

Table 1. Stellar Parameters for TOI-3521

According to its temperature, the host star of TOI-3521.01 is a G-type main-sequence star, also known as a yellow dwarf. The Sun, with an effective temperature of 5780 K, is also a yellow dwarf. The RA and DEC coordinates are essential to our study because they provide us with the exact position of the host star of TOI-3521.01 in the sky.

Using the Mikulski Archive for Space Telescopes (MAST) Portal (5), we also found and extracted a light curve file using data from the TESS mission. We plotted the data via a Jupyter Notebook. We adjusted the x-axis so that one transit is visible at a time of 0.18928808419 TESS Barycentric Julian Date (TBJD).

2.2.

David Ciari of the NASA Exoplanet Science Institute (NExScI) has submitted a speckle sensitivity curve from his speckle imaging observations to ExoFOP (3). His analysis aimed to determine whether or not there are nearby faint stars that could indicate an NEB while determining how well his instrument could detect faint stellar companions. He took multiple short exposures

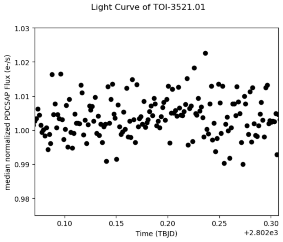

Figure 2. light curve of TOI-3521.01 from TESS data

of the target using the Keck II 10-meter telescope in Hawaii, which he processed into a high-resolution image. The purpose of this was to supersede the blurring effects of Earth's atmosphere on astronomical observations.

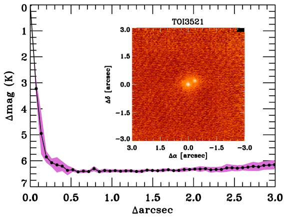

Figure 3. Speckle sensitivity graph submitted to ExoFOP by David Ciari

The inset speckle image shows what seems to be another star in the vicinity of 3521.01. While this could indicate that TOI-3521 is in a binary star system, there could have been a chance alignment of the two stars. Without more data, we cannot be certain whether the former or the latter is true. This uncertainty is another reason we need to evaluate TOI-3521.01 more to determine whether or not it is a genuine exoplanet.

2.3.

We obtained the raw science images using the 0.8-meter telescope at GMU with the R filter. The observation began on June 17, 2024, at 21:49 EDT and ended at 4:31 the next day. We collected 209 raw science images, each with an exposure time of 90.000 seconds. Before our analysis, we visually inspected each image and discarded fifteen due to streaking and eight due to the field of view shifting.

3. ANALYSIS

Section 3.1 discusses the process of data reducing and plate solving the raw science images. Section 3.2 details the process of performing multi-aperture photometry on the resulting images. In Section 3.3, we explain the process of extracting the light curve of our transit.

3.1.

To use the science images collected, we first had to subtract the dust and thermal noise that obscured our field of view. We did this by removing those same obstructions captured in flat and dark images. First, we median combined the dark and flat images. Then, we dark subtracted our median-combined flatfield image using a median-combined dark image with the same exposure time of 3.000 seconds as our raw flat images. Then, we normalized the resultant image. We also dark subtracted our raw science images using a median-combined dark image with the same exposure time as the raw sciences. Finally, we divided our dark-subtracted science images by the normalized dark-subtracted flatfield to obtain our reduced science images for plate solving and multi-aperture photometry.

To determine how we oriented the telescope in the sky, we used the plate-solving method via AIJ and a local form of Astrometry.net software. This automated process involved comparing the field of stars in our science images to a database of stars and their coordinates, which allowed us to ensure that the observed transit is indeed occurring on the host star of TOI-3521.01.

3.2.

To determine the correct aperture size for our multi-aperture photometry, we produced a seeing profile of our target star. We used the consequent value for the radius (30.00) as our aperture size, while we used the inner (52.00) and outer (78.00) radii of the background as our annulus sizes. These parameters ensure that the apertures collect all of that star's light without including background noise.

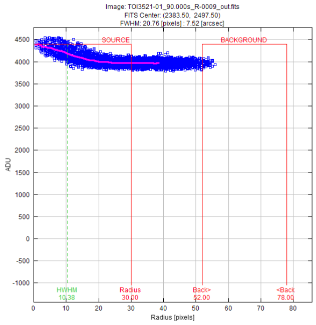

Figure 4. Seeing profile of TOI-3521 generated by AIJ

We then overlaid a file with RA and DEC coordinates of stars within a 2.5' radius of our target. We obtained this file via the Gaia mission, which seeks to create the most extensive three-dimensional map of the Milky Way(4). This tool allowed us to identify local stars we later used to check for NEBs. Then, we manually chose reference stars of approximately the same brightness and magnitude as our target star.

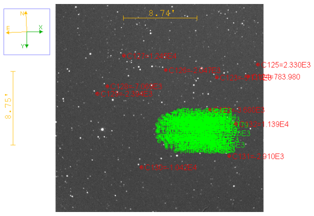

Figure 5. Field of view image with the stars we chose as references in red and the rest in green

The purpose of the multi-aperture photometry was to quantify the amount of flux coming from our target star over time compared to other nearby stars over the observing period. Choosing potential reference stars allowed us to compare our target star to a baseline flux. This comparison was necessary to produce an accurate model of the transit of TOI-3521.01. From our apertures, we created a measurement table for the flux of our target star over time.

3.3.

AIJ's plotting tools allowed us to create a light curve using the aforementioned measurement table. We began by uploading a plot configuration template so that all plotting windows are per TESS's guidelines. Then, we plotted the raw flux of TOI-3521, the transit model, and the corresponding residuals. Also, we plotted multiple detrending parameters in the same window. Then, we reviewed all chosen reference stars to see if any had an unusual variance that would interfere with the accuracy of our light curve. All had minimal variance, so they were all kept as reference stars.

Next, we ran an NEB check to determine whether or not stars in the vicinity of our target were potential sources of false positives. As seen in Figure 5, none of the Gaia stars were below the cleared boundary (in green) or the nearly cleared boundary (in magenta). Since none of the stars were cleared, our NEB check was inconclusive. Consequently, we cannot be sure an eclipsing binary rather than an exoplanet didn't cause the apparent transit of TOI-3521.01.

Afterward, we adjusted our light curve's left and right bounds to match the transit pattern displayed. In our case, the predicted ingress time was 0.682 Barycentric Dynamical time (TDB), while our light curve suggested it was 0.672. Similarly, our predicted egress was 0.741 TDB, while our light curve suggested it was 0.745 TDB. We also tried using different detrending parameters to obtain a model that best fit the data. Using only the AIRMASS detrending parameter, which considers the observing environment's transparency, yielded the most favorably fitting transit model.

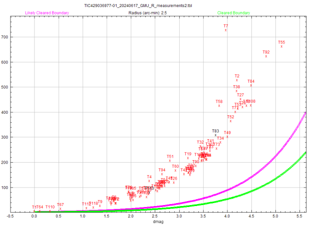

Figure 6. RMS vs. dmag plot for NEB check

4. RESULTS

Here, we present the final light curve obtained for the transit of TOI-3521.01. Then, we present statistical metrics of our transit model according to the chi-squared goodness of fit test and the predicted radius of TOI-3521.01.

Predicted Planetary Radius (R_{Jup})	0.88
Calculated Transit Duration (Days)	0.069262
RMS (ppt)	5.08
Chi-squared Statistic	62.2324
Degrees of Freedom	40
Reduced Chi-Squared Statistic	1.555811
P-Value using reduced Chi-Squared Statistic	0.21228

Table 2. Physical and statistical results from the light curve

5. DISCUSSION

The transit of TOI-3521.01 occurred in a similar but slightly longer span than predicted. However, because the data is so sparse at these points, it makes sense why the model's predicted ingress and egress times would be slightly off. The calculated depth of the transit was 9.06 parts per thousand (ppt), which is fairly consistent with the expected depth of 10.7 ppt.

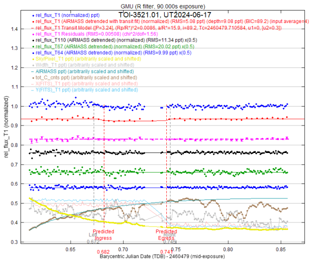

Figure 7. The light curve of the transit of interest, detrended using the Airmass parameter

The root mean square (RMS) value is a measurement of error that takes the standard deviation of the residuals from our transit model. Our model's RMS of 5.08 is very reasonable, especially for observations taken at a college campus where there are nearby sources of artificial light. This speaks to the consistency of our observation with that of TESS.

A chi-squared goodness of fit test assesses how well our transit model fits the data by dividing the square of the difference between our actual and expected data by our expected data. The reduced chi-squared statistic, the ratio between the chi-squared statistic and the degrees of freedom, should be as close to 1 as possible. A reduced chi-squared statistic of 1 would mean that our data is as expected for each "bin" of data. Our reduced chi-squared statistic of about 1.56 shows that the data fit the model reasonably well. The P-value of our reduced chi-squared statistic is above a significance level of 0.05, which confirms that the discrepancies between the data and the transit model are not statistically significant. If we had not had to remove so many of our science images and thus had more data for our light curve, the fit would likely have been even better.

Since the transit detection method is biased towards planets that block out more of their star's flux, it makes sense that gas giants with extremely close orbits, called hot Jupiters, are common among TESS candidates. Because TOI-3521.01 would have a radius 0.88 times that of Jupiter and an orbital period of around three days, it would fit into this category if it were not a false positive.

However, we must be cautious about deeming this candidate a genuine exoplanet due to our inconclusive NEB check. Furthermore, the other star shown in Figure 3 indicates that we should be even more careful in ruling out the possibility of an eclipsing binary. Therefore, it is ultimately unclear whether or not we have a genuine exoplanet. Ultimately, further research is needed to finalize the status of TOI-3521.01.

6. CONCLUSIONS AND FURTHER WORK

We obtained raw science images by using ground-based observations of TOI-3521 via GMU's 0.8-meter telescope. After data reducing and plate solving these images using AIJ, we performed multi-aperture photometry to plot a light curve of the transit of TOI-3521.01. The results suggest that the possibility of the detection being a false positive is not out of the question but that TOI-3521.01 appears to be a hot Jupiter.

In the future, we may conduct a more conclusive NEB check to investigate further the likelihood of TOI-3521.01 being a false positive. We would achieve this by repeating the procedure in this study using a larger telescope with deeper exposures. Furthermore, we could collect more data on a night when there is less atmospheric noise to see if we can obtain a transit model with more usable data and a better fit. We could also run a Bayesian statistical analysis to get a more in-depth look at the probabilities of TOI-3521.01 being a false positive.

Additionally, it may be helpful to use Doppler spectroscopy to validate what the transit suggests. It provides a convenient detection method for ground-based telescopes like the one at GMU because we do not need to continuously monitor the target star. Furthermore, if TOI-3521.01 is a genuine exoplanet, Doppler spectroscopy would estimate the minimum mass of TOI-3521.01. This information would provide a lower bound for its density, giving insight into its composition. Knowing clues about its mass, density, and composition would give us more confidence in classifying TOI-3521.01 as a hot Jupiter, further adding to our vast information about exoplanet populations.

7. ACKNOWLEDGMENTS

The author is honored to learn about exoplanet astronomy about exoplanet astronomy from an accomplished professor in the field, Dr. Peter Plavchan. She would also like to thank George Mason University for facilitating this unique opportunity.

This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

This research has made use of the Mikulski Archive for Space Telescopes (MAST).

REFERENCES

[1]Clark, J. T., Addison, B. C., Okumura, J., Vach, S., Errico, A., Heitzmann, A., Rodriguez, J. E., Wright, D. E., Mathieu Clerte, Brown, C. J., Fetherolf, T., Wittenmyer, R. A., Plavchan, P., Kane, S. R., Horner, J., Kielkopf, J. F., Avi Shporer, Tinney, C. G., Liu, H.-G., Ballard, S. (2023). Spinning up a Daze: TESS Uncovers a Hot Jupiter Orbiting the Rapid Rotator TOI-778. The Astronomical Journal, 165(5), 207–207. https://doi.org/10.3847/1538-3881/acc3a0

[2]Collins, K. A., Kielkopf, J. F., Stassun, K. G., Hessman, F. V. (2017). ASTROIMAGEJ: IMAGE PROCESSING AND PHOTOMETRIC EXTRACTION FOR ULTRA-PRECISE ASTRONOMICAL LIGHT CURVES. The Astronomical Journal, 153(2), 77.

https://doi.org/10.3847/1538-3881/153/2/77

[3]ExoFOP TIC 429036977. (2015). Caltech.edu. https://exofop.ipac.caltech.edu/tess/target.php?id=429036977

[4]Gaia - NASA Science. (n.d.). Science.nasa.gov. https://science.nasa.gov/mission/gaia

[5]Mikulski Archive for Space Telescopes (MAST) Portal. (n.d.). Mast.stsci.edu. https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

[6]NASA. (2019, February 25). Transiting Exoplanets Survey Satellite (TESS) - Exoplanet Exploration: Planets Beyond our Solar System. Exoplanet Exploration: Planets beyond Our Solar System. https://exoplanets.nasa.gov/tess/

[7]Rodriguez, J. E., Quinn, S. N., Vanderburg, A., Zhou, G., Eastman, J. D., Thygesen, E., Cale, B., Ciardi, D. R., Reed, P. A., Oelkers, R. J., Collins, K., Bieryla, A., Latham, D. W., Gonzales, E. J., B Scott Gaudi, Hellier, C., Jones, M. I., Brahm, R., Sokolovsky, K., Schulte, J. (2023). Another shipment of six short-period giant planets from TESS. Monthly Notices of the Royal Astronomical Society, 521(2), 2765–2785. https://doi.org/10.1093/mnras/stad595

[8]TESS. (2018). TESS - Transiting Exoplanet Survey Satellite. https://tess.mit.edu/science/

[9]TESS Ground Based Follow-up Program. (2024). Nasa.gov. https://asd.gsfc.nasa.gov/archive/tess/ground$_{b}ased_{f}ollowup.html$

[10]TOI-3521 — NASA Exoplanet Archive. (2021). Caltech.edu. https://exoplanetarchive.ipac.caltech.edu/overview/TOI-3521.01