

GROUND-BASED LIGHT CURVE FOLLOW-UP VALIDATION OBSERVATIONS OF TESS OBJECT OF INTEREST TOI 3945.01

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ABSTRACT

The following paper covers the follow-up validation observations of the TESS Object of Interest (TOI) 3945.01 using images taken by the 0.8m telescope located on the George Mason University campus. The respective images of this TOI were then used to distinguish whether this candidate can be confirmed as an exoplanet or a false positive as part of the TESS Follow-up Observation Program (TFOP). The TESS mission, which aims to find and validate possible exoplanet contenders, has searched through over 200,000 stars near the sun and has found over 7,200 possible contenders as of June 26th, 2024 since its launch in April of 2018. Only 475 exoplanets have been confirmed out of these contenders. (Nowakowski, 2024). The goal of this research is to provide a ground-based follow up validation of the proposed exoplanet TOI 3945.01 and to confirm whether it is a transiting exoplanet or a false-positive, in this case most likely a nearby eclipsing binary (NEB). We carried out the research by using the application AstroImageJ to data reduce and plate-solve various darks, flats, and sciences taken by the George Mason University 0.8m telescope on the night of June 25, 2024. Following the plate-solving process, aperture and multi-aperture photometry allowed us to determine a light curve of our target. The following light curve provided us with more information about the planet including its p-value and other relevant statistics such as Research was carried out using the application AstroImageJ and a light curve was generated. Failed NEB checks and examinations of the outliers do not prove that there are no NEBs present, however NEB signals seemingly are not detected. Further work and research would have to be done to verify the presence of a planet, but the light curve is the first step forward in improving this research. If the planet were to exist, it would be classified as a hot Jovian planet due to its sub-10-day orbital period and radius (R_{earth}) of 9.59744.

1. INTRODUCTION

The TESS (Transiting Exoplanet Surveying System) mission aims to find exoplanets in the near universe by measuring the brightness of the nearest 200,000 stars surrounding our solar system. TESS uses a total of four CCD

cameras to collect this light in 30 observation sectors that are each 24 degrees wide by 96 degrees long. It takes on average at least 27 days to fully observe each of the 30 sectors. The cameras capture important data at a high

cadence, and exposures of targeted objects obtained every 2 minutes with full frame images are yielded every 30 minutes. (Ricker, 2015). After this valuable data is received, the process for finding exoplanets from these candidates can begin. But first, why look for exoplanets? The first exoplanet orbiting a star like our Sun was discovered in 1995 and since then, we have not stopped looking. The search for exoplanets gives us important insight into the creation and habitability of other worlds, which can help us better understand the

Although there have been previous accounts of TOI 3945.01, no papers have been written about it, making this research particularly necessary to understand more about this candidate. Early work on other TOI's have paved the way for other astronomers to learn more about them, and this paper is a good first step. This work is directly addressing the unknown and the open ended questions we still have about exoplanets.

In this paper, we present follow-up observations of TOI 3945.01 (TIC 336824844.01). The target planet has a radius of about 9.59744 (R_{earth}), a period of around 4.46 days, and an expected duration of about 1.556 hours. It has a depth of about 3791 ppm and it is known to orbit a yellow dwarf G-class star¹ (Stellar effective temperature of 5472 K) with a radius of 1.42262 (R_{sun}). (EXOFOF, 2023). Our goal is to investigate whether or not the transit occurs on the expected star at the expected time, with the expected duration and depth.

creation of our own planet, and possibly even help us figure out where humans came from (The European Space Agency, n.d.). Confirming exoplanets is no easy task, but some methods include looking at radial velocity, transits, transit spectroscopy, and gravitational microlensing, however the most common method is looking at the transit of a star. This involves measuring the dips in light coming from a star over a period of time, and from this, the orbital size of the suspected planet can be determined based on the period and the mass of the star.

In Section 2, we present our Observations from TESS and the George Mason University 0.8m telescope. In Section 3, we present our analysis of the TESS light curve for TOI 3945.01 and our ground-based light curve analysis. In Section 4, we present our light curve results. In Section 5 we discuss our results and in Section 6 we present our conclusions and future work.

2. OBSERVATIONS

In Section 2.1 we present the TESS Object of Interest 3945.01 and its exoplanet candidate properties, its host star properties from the TESS Input Catalog, the Gaia mission, and other archival sources. In Section 2.2 we present the TESS sector light curve(s). In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

SECTION 2.1

The TOI 3945.01 was first ground-observed around June 24th, 2021. The proposed planet has a Transit Epoch (BJD) of 12.5917 and a depth (mmag) of about 4.123848. It also has a radius (R_{earth}) of around 9.59744, a period

1 - Australia Telescope National Facility. (2024, March 6). Classifying stars - the Hertzsprung -Russell diagram. Classifying Stars - The Hertzsprung -Russell Diagram. https://www.atnf.csiro.au/outreach/education/senior/cosmicengine/stars_hrddiagram.html#

of around 4.46 days, and an expected duration of about 1.556 hours and a depth of about 3791 ppm. The planet has an equilibrium temperature of 1336 Kelvins and orbits a star similar to our own Sun, having a radius (R_{sun}) of 1.42262 and a stellar effective temperature of 5472 Kelvins. The star has a mass (M_{sun}) of 0.96. The coordinates for this star include a right ascension (RA) of 12h29m43.04s and a declination (DEC) of -58d14m24.47s (ExoFOP 2024).

SECTION 2.2

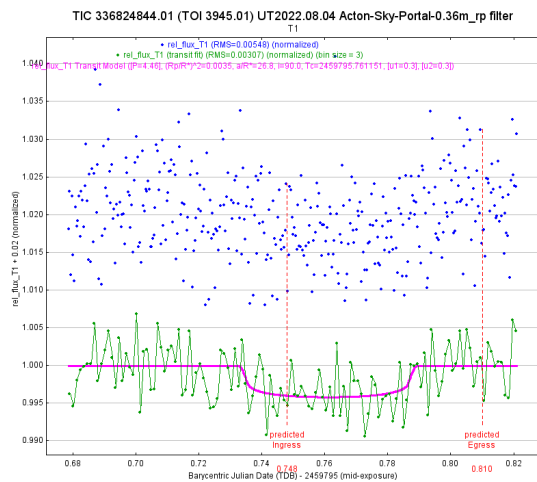


Figure 1: Light curve of TOI 3945.01 taken by Paul Benni on August 8th, 2022

SECTION 2.3

On June 25th, 2024, the George Mason University 0.8m telescope was used to photograph our target, collecting 199 total sciences, along with ten 3s exposure darks and ten 90s exposure darks. A total of ten 3s exposure flats were taken as well, and all were taken with the R filter. These images were taken over the course of several hours, starting at 21:50 on June 25th, 2024 and ending at 04:33 on June 26th, 2024, Eastern Time. Next we inspected each science for any irregularities. Throughout this process,

58 images had to be removed due to streaking, as well as occasional shifts to the field of view resulting in blurry and distorted stars. From this inspection resulted in a total of 141 images eligible for usage.

3. ANALYSIS

In Section 3.1 we present our tools used to analyze the TESS sector light curve(s) curves using AstroImageJ. In Section 3.2, we present our analysis of the ground-based light curve using AstroImageJ.

SECTION 3.1

The full analysis and generation of the light curve was done using AstroImageJ as well as information from ExoFOP and the NASA Exoplanet Archives. After the sciences were inspected, we used AstroImageJ's CCD Processor feature to data reduce the images. The result was images that have been cleared of background noise. After data reduction, we combined darks into a master dark file and flats into a master flat file for easier usage when plate solving. After that, we plate-solved the sciences using Astrometry.net as well as AstroImageJ to ensure that our target was in sight and aligned. The plate solving process also allows us to know exactly where in the sky the telescope is pointed at. After plate solving, we inputted the RA and Dec coordinates to be able to find our star on the image.

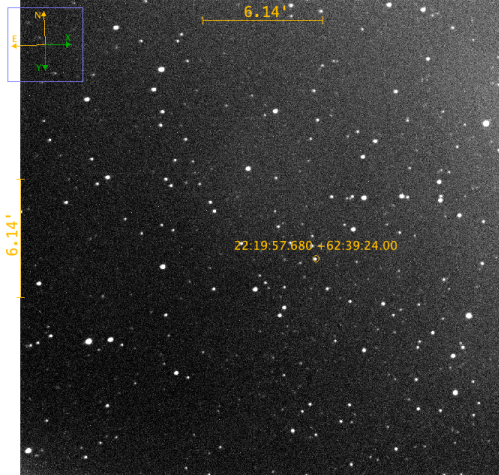


Figure 2: Example of target star highlighted after inputting RA and Dec coordinates.

After the target was found, we created a seeing-profile to be able to visualize the suggested pixel radius (aperture size) of the target. The inner and outer radius sizes were also determined by the seeing profile, which helped us determine our annuli radius values.

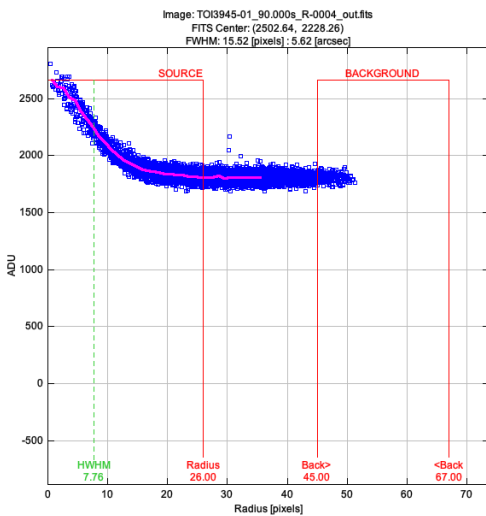


Figure 3: Seeing Profile generated that shows the pixel radius of 26.00 at the bottom, including the inner radius of 45.00 and the outer radius of 67.00.

Following the seeing profile, we then created a temporary 2.5' circle around our target which helped us determine the closest stars to our target. Afterwards, we applied a Gaia stars .radec file to see the stars surrounding the target. 10 stars were manually chosen as reference stars during multi-aperture photometry.

SECTION 3.2

Then, we started the light curve generation process. First, we uploaded a plot configuration file that helped us standardize our plot so it was in compliance with TESS/K2 reporting guidelines (Conti, n.d.). Next, we entered the predicted ingress (0.628) and egress (0.690) times into the Multi-plot Main window, which controlled the size of the plot. We also adjusted the titles of both axes in this window.

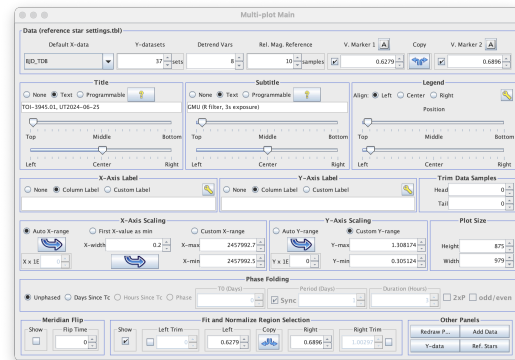


Figure 4: Final Multi-plot Main window featuring plot technicality settings

In a different window, Data set 2 fit, we entered the orbital parameters as well as host star parameters and transit parameters obtained from the NASA Exoplanet Archive and ExoFOP databases. We also entered Linear LD u1 and Quad LD u2 values into the window provided from the EXOFAST -

Quadratic Limb Darkening applet (Eastman et al. 2013). Following this, we plotted detrending parameters AIRMASS, Sky/Pixel_T1, Width_T1, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1 to accordance with the guidelines provided in the TFOF SG1 Observation Guidelines (Conti, 2020). After doing this, we then checked and examined the flux of each reference star. Reference star C234 was removed from the Multi-plot Reference Star Settings window due to a large flux.

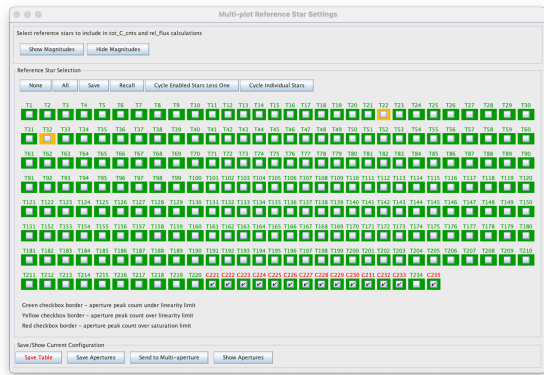


Figure 5: Final Multi-plot Reference Star Settings window with C234 unchecked.

Afterwards, one reference star was chosen to represent a basis for what a standard star without a transit would look like on the graph. Reference star C235 was chosen and was detrended with AIRMASS parameters. The candidate planet’s light curve was then detrended with AIRMASS and tot_C_cnts parameters, and an NEB check was performed next.

4. RESULTS

In Section 4.1 we will provide the resulting NEB check. In Section 4.2, we will provide the final generated light curve results.

SECTION 4.1

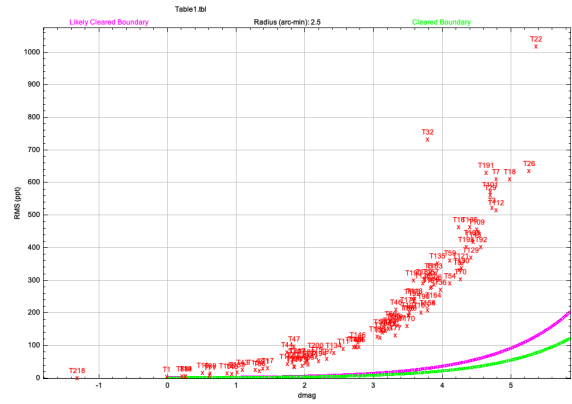


Figure 6: Resulting NEB Check dmag vs. RMS (ppt) plot

The plot above is the result of completing the NEB check. It is apparent that no stars passed the NEB check since each star is to the left of the magenta “Likely Cleared Boundary” line. However, there seems to be a curved shape that the stars follow, meaning that the failure of the NEB check could be due to suboptimal exposure times for observing NEBs.

SECTION 4.2

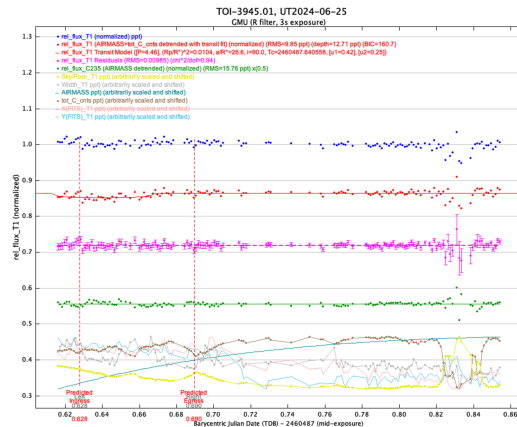


Figure 7: The image above shows the final resulting light curve of the target after applying detrending parameters.

Figure 7 shows a visible dip in the light curve of the target. The dip does not fully line up with the predicted ingress and egress lines with data taken from the NASA Exoplanet Archives and the ExoFOP databases, however it appears to start earlier and end around three-quarters in between the ingress and egress lines.



Figure 8: Final Data set 2 fit window that features the final settings and data points of the light curve

As visible on the Data set 2 fit window, the transit has a depth (ppt) of 12.71, a transit duration (hms) of 01:24:46, and an RMS (ppt) value of 9.853452. The model also shows a chi squared value of 126.0392 and a 134 degrees of freedom (dof).

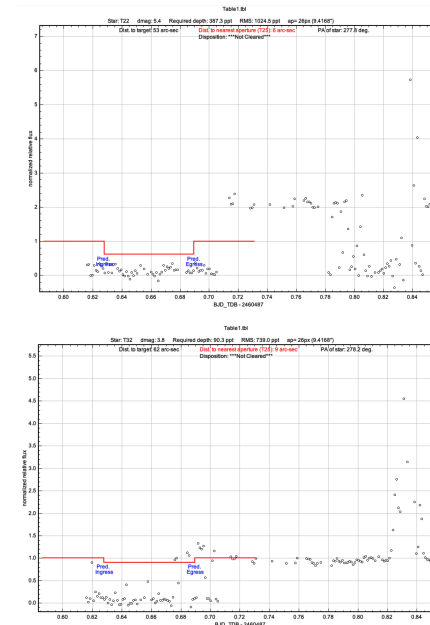
5. DISCUSSION

In Section 5.1 we present our interpretation of our NEB Check. In Section 5.2 we present our interpretation of our light curve and Data set 2 fit window. In Section 5.3 we

place our results into context of the greater field of follow-up of candidate exoplanets from the NASA TESS mission.

SECTION 5.1

As seen in Figure 6, none of the stars successfully cleared the NEB check, meaning that there is still a possibility for a NEB (Nearby Eclipsing Binary) however, the two apparent outliers, T22 and T32, the reference stars most likely to have an NEB, did not present obvious signals of an NEB.



Figures 9.1 and 9.2: Top: the NEB light curve plot for T22, Bottom: the NEB light curve plot for T32

Without all the reference stars fully clearing the NEB check, it is difficult to determine whether there is actually a planet at our target star.

SECTION 5.2

Following the examination of an NEB, we also examined the values on the Data set 2

fit window as well as the light curve itself (Figures 8 and 7, respectively). The transit duration (t14 hms) was around 01:24:46, which happened to match with the expected duration of $01:23 \pm 0:26$. This transit is relatively on time, meaning that there is a chance of a planet. The predicted start of the transit also occurs around 23:04 and the end occurs around 00:33 with a margin of error $\pm 1:01$ which means that the light curve we see is likely the light curve of the candidate exoplanet. The Data set 2 fit window also includes the depth in ppt, which can easily be converted to ppm by increasing ppt by a factor of 1000. When this is done, the depth is 12170 ppm, which is completely off of the expected depth in ppm, 3791 ppm (ExoFOP, 2024). The 12.71 ppt depth can also be turned into mmag depth by multiplying by 1.0836, however that value of 13.772556 is still far off the expected depth in mmag, which is 4.123848. (Conti, 2020). A possible reason for this depth could be that TESS underestimated the size of the planet or that light was diluted when measuring the depth.

Using the chi squared value of 126.0392 and the dof value of 134, we calculated a p-value ≈ 0.67556 , which, based on a significance level $\alpha = 0.05$, proves that the result is statistically not significant, or that we do not have enough evidence to reject the null hypothesis. Our null hypothesis is that there is not a significant difference between our observed data and the expected data, so that means that our light curve is close to what the TESS mission has already expected for a light curve. Overall it is difficult to determine whether this TOI is a false positive or not considering that our NEB

check has not provided us with any NEBs but has not denied the chance of an NEB. Furthermore, values such as the depth (ppt) do not align with what is expected from ExoFOP databases, so the result of this research is an inconclusive result on whether TOI 3945.01 is a confirmed planet or not.

SECTION 5.3

Although it cannot be a confirmed planet, based on the data given from the ExoFOP databases and the NASA Exoplanet Archive, we can attempt to classify the type of planet this TOI would be if confirmed a planet. Looking at the planetary temperature and size on ExoFOP, we can determine that this planet would be considered a Jovian planet considering its massive size, however it is still slightly less than the size of Jupiter, with a radius (R_{earth}) of 9.59744 (Kopparapu et al 2018). The orbital period is also 8.41 days according to the NASA Exoplanet Archive, meaning that this planet would be considered “hot” since it has an orbital period of less than ten days, showing that it is close to its star (Wang, et al. 2015).

6. CONCLUSIONS & FUTURE WORK

Overall, we could not determine whether TOI 3945.01 was a false positive or an actual planet, and more work would have to be done to find clear results, such as possibly using a different method such as radial velocity and spectroscopy. To ensure that this planet is or is not a false positive, a more in-depth NEB check would have to be done with exposure times specifically for detecting NEBs. This would require using larger telescopes that are capable of longer exposure times to more accurately measure brightness. This research provides the first

step to learning more about this candidate and provides a light curve with details that may be helpful for future research.

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