Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest TOI 3945.01

Peter Plavchan[1], Hanseon Lee[2], S Falgiano[1], Owen Alfaro[1], Kevin Collins[1]

[1]Department of Physics and Astronomy, 4400 University Drive MS 3F3, George Mason University, Fairfax, VA 22030, USA
[2]Thomas Jefferson High School for Science and Technology, Alexandria, VA 22312, USA

Abstract

Transiting exoplanet survey satellite (TESS) is the leading discoverer of exoplanets using the transit method. As TESS reports any potential exoplanet candidates, follow-up observations are necessary to determine the identity of the TESS object of interest (TOI). In this paper, we aimed to confirm if the transit on TOI-3945.01 occurred between the predicted ingress and egress time, duration, and depth. Additionally, we attempted to investigate the planet type of TOI-3945.01 based on its properties. The data was gathered at the George Mason University (GMU) observatory using an R filter, obtaining 199 sciences each with 90 seconds of exposure. We performed data reduction, light curve production, and NEB check using AstroimageJ. Our light curve of TOI-3945.01 displayed slight dips in flux corresponding to the light curve generated by TESS, suggesting the likelihood that our target is a real positive. The NEB analysis did not show any definitive results, leaving potential signal disruption from NEB's unknown. Further investigations with detailed statistical analyses are essential to establish a thorough conclusion regarding TOI-3945.01's identity.

1. Introduction

The study of exoplanets has significantly contributed to understanding outer space and detecting potential signs of life and inhabitable planets. Thanks to the extensive advancements in technology and science, astronomers have confirmed more than 5,000 exoplanets to date[1]. The Transiting exoplanet survey satellite (TESS) mission has been crucial to discovering exoplanets, confirming 491 detected planets[1]. TESS employs the transit photometry method, which has proven its effectiveness by finding 75% of all confirmed exoplanets[2]. The "transit" method examines the flux of a star in the passage between the observer and the star. When a planet partially or fully blocks the path of the light emitted from its host star, a decrease in brightness occurs. The degree at which the brightness declines is used to determine the existence of a stellar object nearby the star, which is most likely that of a planet in the system. This simple, yet efficient method easily allows astronomers to detect exoplanets and reveal partial information about them. For instance, it provides an estimate of the planet's diameter, which can then be used to calculate the planet's density identified by the radial-velocity method[3]. However, the candidates discovered using transit photometry typically need follow-up observations in order to confirm their identity since they may be actual exoplanets or false positives.

TESS has found 4,648 exoplanet candidates[1], and each of them are named with a unique TOI code (i.e. TOI-3945.01). Ground-based follow-up observations are commonly conducted to confirm these candidates. For instance, a recent study discovered the transiting exoplanet TOI-2447 b, a cool giant of mass approximately equal to that of Saturn[4]. The planet was previously identified as a candidate as supported by its transit event of 1.3% depth and 7.29 h duration. Another study shows the confirmation of TOI-2374 b and TOI-3071 b by utilizing photometry in various follow-up observations[5]. However, due to the vast number of these candidates, numerous planets do not have published papers verifying their identity. Currently, there is no known published study of TESS object TOI 3945.01, and a follow-up observation is necessary to collect more information and ensure its existence.

In this paper, we present the follow-up observations of TOI-3945.01. Although little is known about the TESS object, we have used the following information to proceed with our analysis: radius = 9.7 $R_\oplus$, orbital period = 4.46 days, and transit duration = 1.483 h. The goal of our study is to investigate whether or not the transit occurs on TOI-3945 at the expected time, with the expected duration and depth.

In **Section 2**, we present our Observations from TESS and the George Mason University (GMU) 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 the result of our light curve. In **Section 5**, we discuss our results and in **Section 6** we present our conclusions and future work as needed.

2. Methods

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. **In Section 2.3**, we present a summary of the observational data collected with the GMU 0.8m telescope. In **Section 2.4**, we present our tool used to analyze the TESS sector light curve curves: AstroImageJ. In **Section 2.5**, we present our analysis of the ground-based light curve using AstroImageJ.

2.1 Properties of TOI-3945.01 identified by TESS

TOI-3945.01 was detected by TESS on 2021-06-23 and was assigned a TESS Input Catalog (TIC) number of 336824844[6]. The data was last modified on 2023-05-04. TESS discovered the following information: stellar effective temperature = 5472.000 K, stellar luminosity = 0.2134548 $\log_{10}(L_{\odot})$, stellar density = 0.4700812 g/cm^3, stellar mass = 0.9600000 $M_{\odot}$, and stellar radius = 1.4226200 $R_{\odot}$. Moreover, it was known that the equilibrium temperature = 830 K, orbital period = 4.4638411±0.0000181, planet radius = 9.5974400±0.7329040 $R_{\oplus}$. The transit duration = 1.556±0.323 days with depth = 0.3791000±0.0398382 % and transit midpoint = 2459885.02895900±0.00628377 days[7].

2.2 TESS light curves

TESS also generated a light curve of TOI-3945.01. **Figure 1** presents the relative flux vs phase plot of the target. There was a noticeable dip between the hours of -1.5 and 1.5, suggesting the planet's existence in the system and a short period of its transit. Solely judging from the light curve, there was a high likelihood that the target is a true positive. However, a follow-up observation such as our study was necessary to confirm the target's identity.

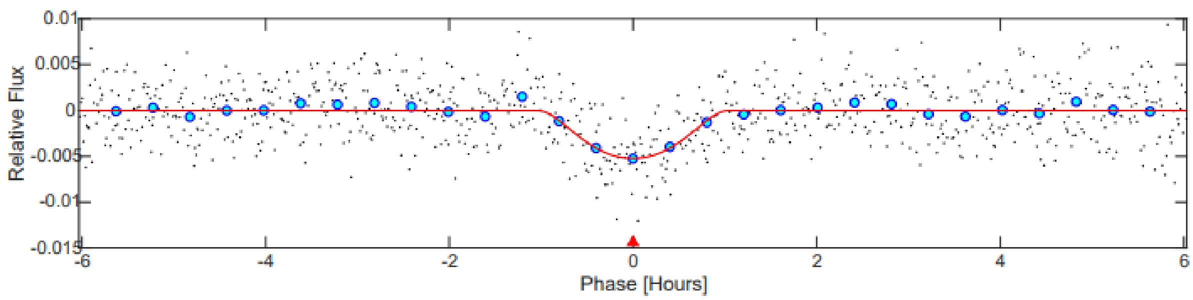


Figure 1. Light curve plot of TOI-3945.01 from the TESS summary report. *Note.* The image was imported from the Mikulski Archive for Space Telescopes (MAST) portal. From Mikulski Archive for Space Telescopes. (n.d.). [A list of observations for TIC 336824844]. https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html.

2.3 Observational data from GMU

The ground-based observation data was collected from GMU observatory, which has an approximate latitude of 38.82818 and a longitude of -77.30535. We obtained 199 raw science images using an R filter, each with an exposure time of 90 seconds. The exposures were completed between 2024-06-26 01:50 - 08:33 UTC. We also collected 20 darks and 10 flats, where 10 science darks each had an exposure time of 90 seconds and the other 10 flat darks and flats each had an exposure time of 3 seconds. The RA and Dec of the target was 22:19:57.62 s and +62:39:23.85 s, respectively.

2.4 AstroimageJ

AstroimageJ is an open-source and java-based software essential in the field of exoplanet detection. It can perform various meticulous tasks for the user including image processing, data reduction, differential photometry, light-curve production, and NEB (Nearby Eclipsing Binary) analysis. Utilizing AstroimageJ allows us to better analyze transits and confirm or invalidate the identity of the candidate planet.

2.5 Analysis using AstroimageJ

The first step to our analysis was to remove defective science images, for example, if it was blurry or containing a satellite obstructing the target. A total of 174 out 199 images remained after elimination. We then subtracted darks from flats, and utilized the master flat and master dark file to process the sciences. The reduced science images were simultaneously plate-solved by employing a user-specific API key provided from nova.astrometry.net[8] with RA and Dec of 22:19:57.62 s and +62:39:23.85 s, respectively, as stated in **Section 2.3**.

After the images were ready for analysis, we began extracting a light curve of TOI 3945.01. The target had an aperture radius of 35.00 px and an inner and outer annulus radius of 61.00 px and 91.00 px, respectively—see **Figure 2** to view the seeing profile. Next, we performed a multi-aperture photometry and imported a Gaia stars file to select 231 reference stars—refer to **Figure 3** to see the fieldview containing the reference stars. These chosen stars have a similar size and brightness as TOI 3945.01. We created a measurement table containing information about the target and these nearby stars that are necessary to generate the light curve.

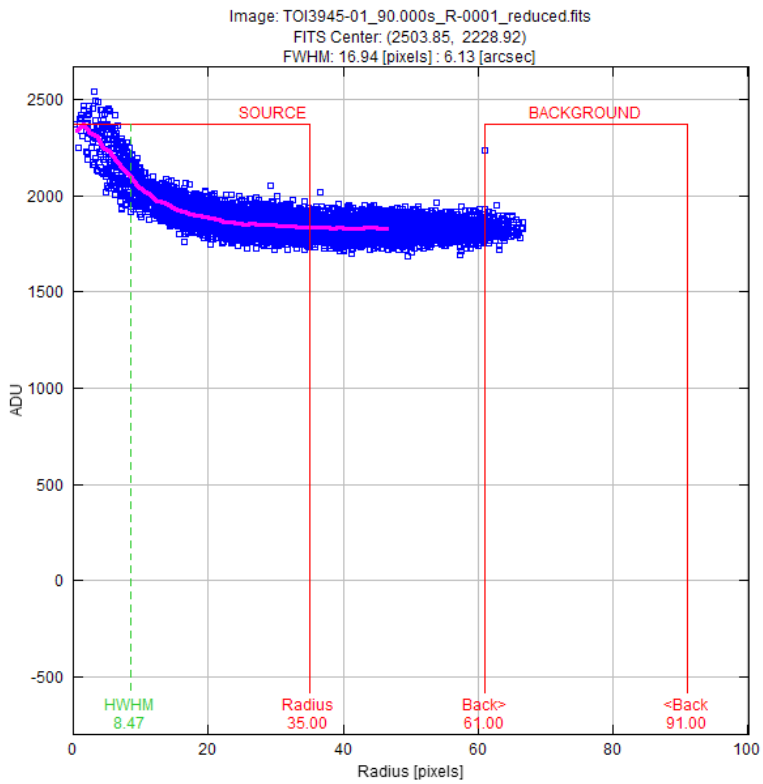
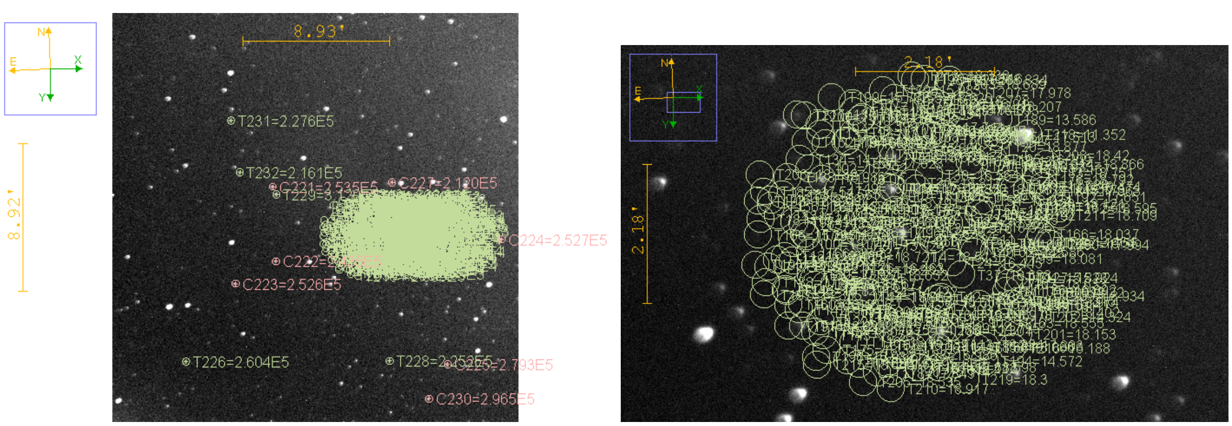


Figure 2. Seeing-profile of TOI-3945.01. *Note.* The radius value of the aperture is indicated under "Radius" and that of the inner and outer annulus radius is indicated under "Back>" and "<Back", respectively.



(a) **(b)**

Figure 3. Field images with apertures. *Note.* (a) has reference stars congested near TOI-3945.01, causing legibility issues. Hence, (b) provides a zoomed-in fieldview within a radius of 2.5 arcmin around the target star.

We began the light curve generation by inputting the data we obtained from TESS. First, we entered the predicted ingress and egress times—0.6279 and 0.6896, respectively, in relative BJD_{TDB}—as well as linear and quadratic limb darkening coefficient values—0.41951083 and 0.24976906, which were fitted to 0.419510830 and 0.249769060, respectively. We then plotted the flux measurements of TOI in different parameters: Sky/Pixel_T1, Width_T1, AIRMASS, tot_C_cnts, X(FITS)_T1, Y(FITS)_T1. We also plotted the light curves of the reference stars and removed them from the list if their flux displayed a large variation or scattering. The final selection of the reference stars is shown in **Figure 4.** Finally, we conducted an NEB analysis to consider the potential that a nearby eclipsing binary interrupted with the signal.

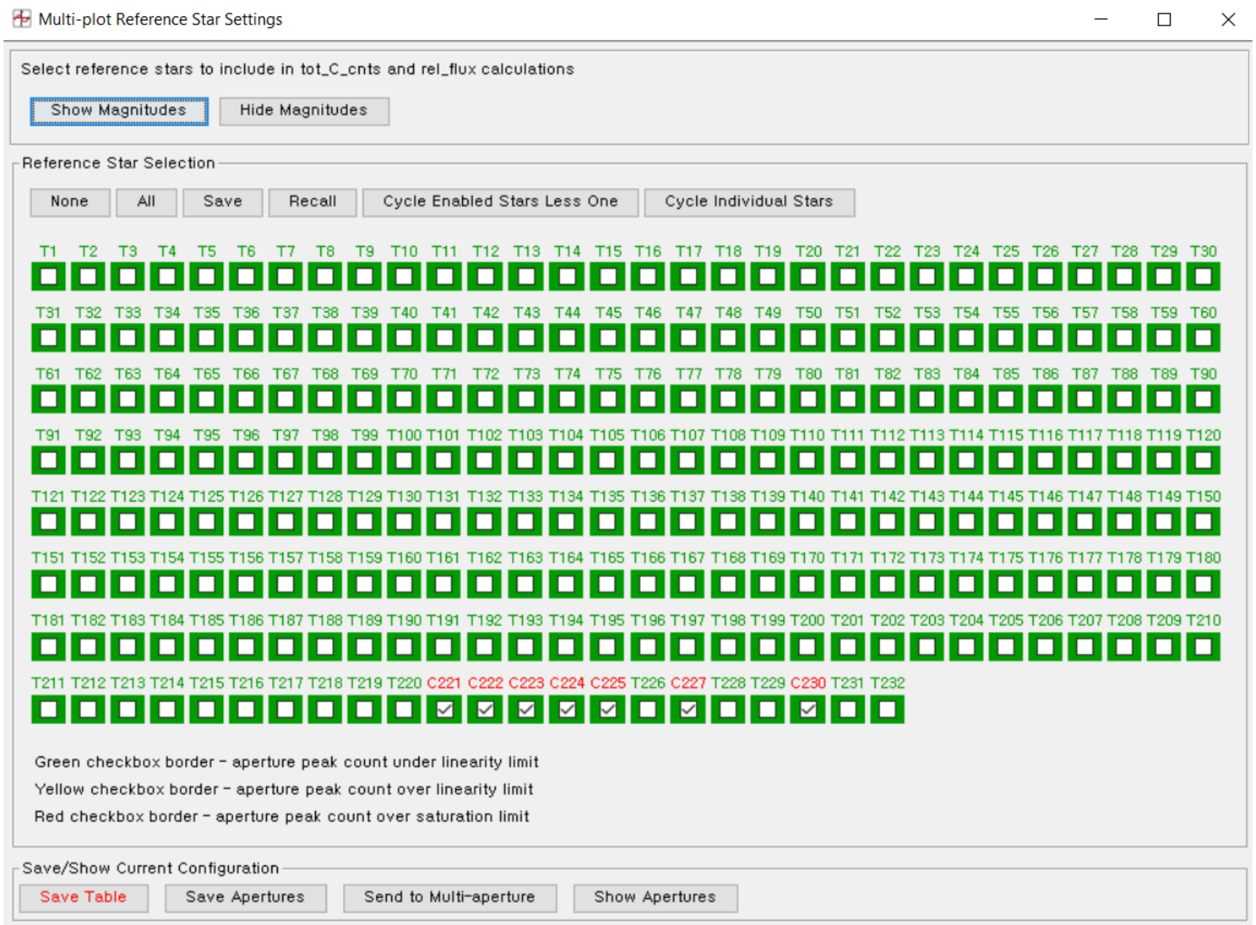


Figure 4. The final selection of reference stars. *Note.* The selected reference stars are indicated by the check marks. “T” denotes the star is not being used as a reference while “C” denotes that it is.

3. Results

In **Section 3.1**, we present our light curve of TOI-3945.01. In **Section 3.2**, we present the NEB tables.

3.1 The light curve of TOI-3945.01

We plotted multiple light curves incorporating various detrend parameters and y-data, each represented by a unique color—refer to **Figure 5**. The plots are as follows: the normalized flux of T1 (blue), the relative flux of T1 detrended with Y(FITS) in a transit model (red) and its residuals modeled with a chi^2 test (pink), the normalized fluxes of comparison stars C224 (black) and C225 (green) both detrended with AIRMASS, the mean pixel value within the sky-background annulus for T1 (yellow), the mean of the X- and Y-direction FWHM (Full Width at Half Maximum) of T1 (light gray), airmass of T1 at mid-exposure (teal), the sum of all comparison star net integrated counts (brown), X- (pink) and Y- (light blue) locations of the center of T1's aperture in Fits coordinate.

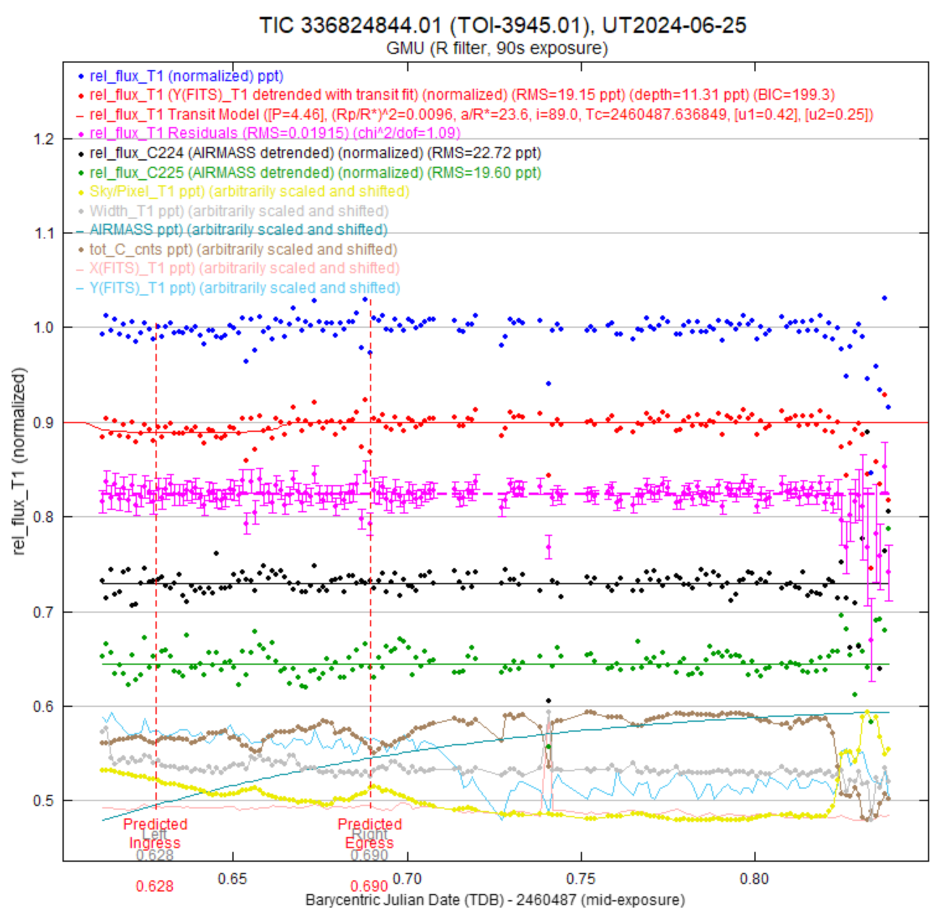


Figure 5. The light curve of TOI-3945.01.

3.2 NEB analysis

The NEB analysis produced a dmagRMS-plot—refer to **Figure 6—**and light curves for each of the 218 nearby stars—refer to **Figure 7**. All the dispositions of the stars were not cleared: 138 dispositions of the stars were not cleared due to low amounts of flux and the 78 of them simply did not meet any conditions for clearance.

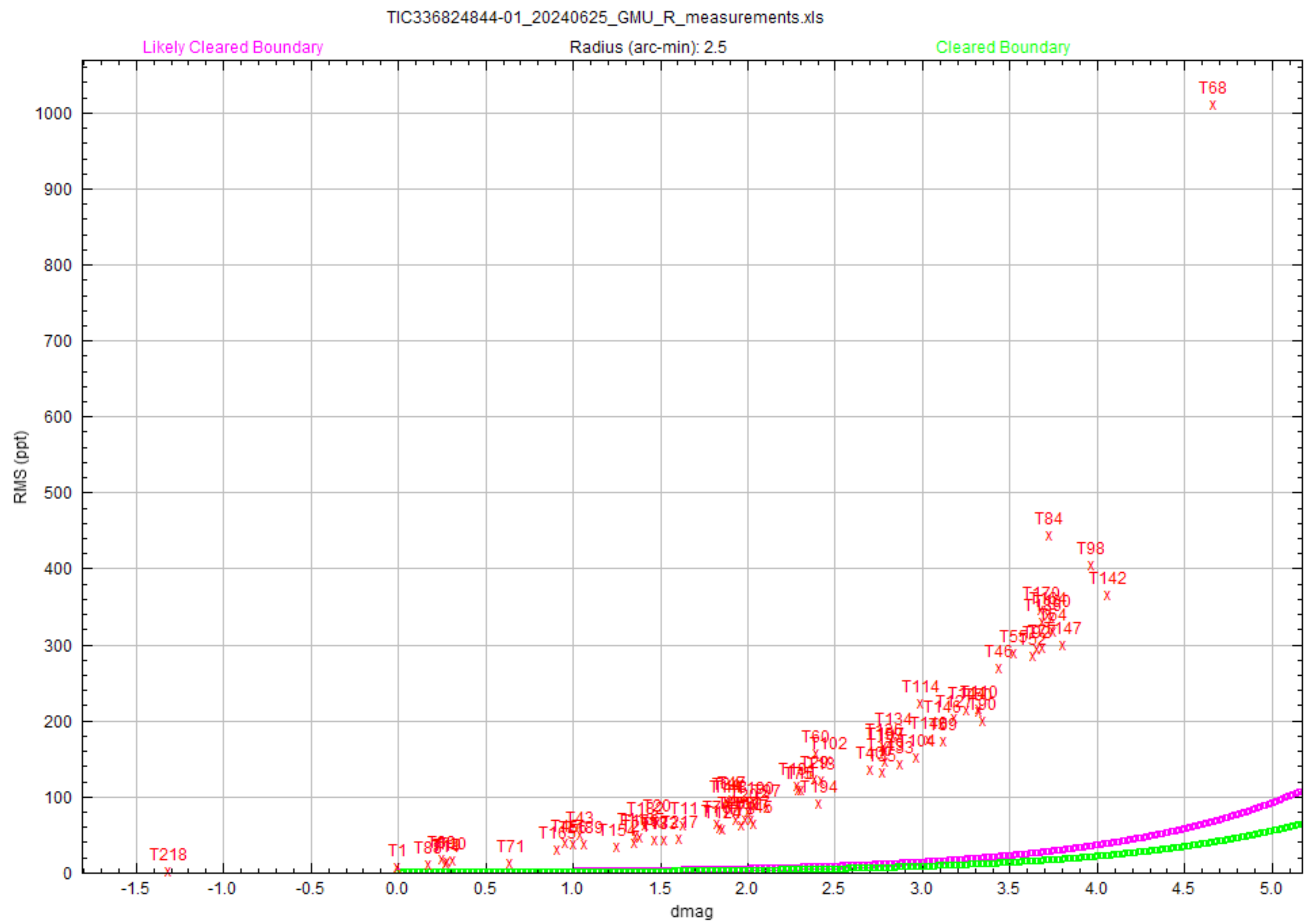
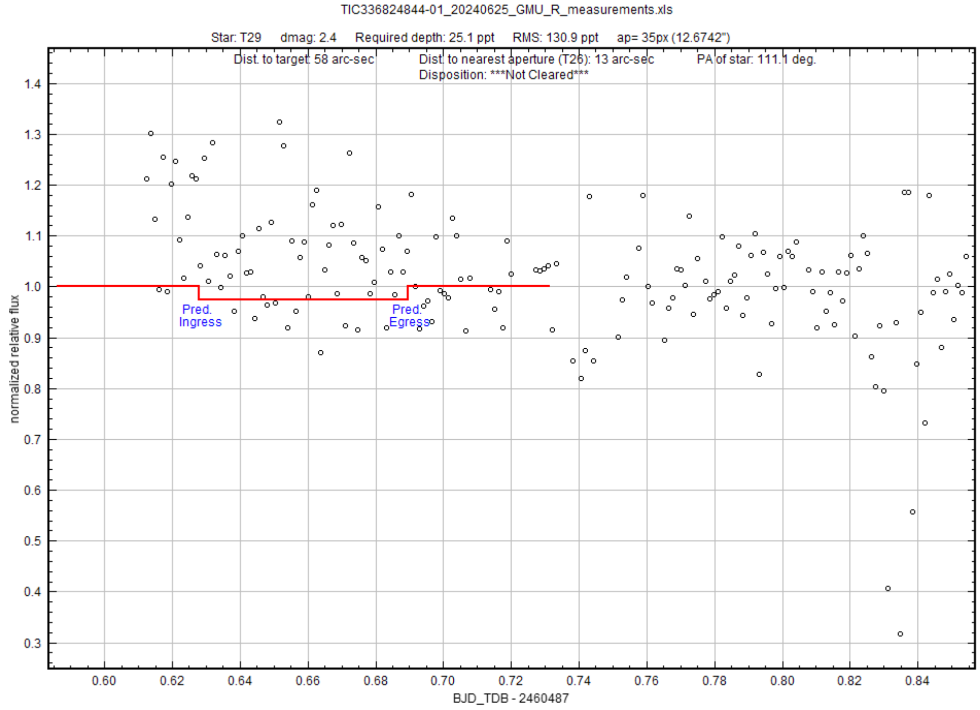
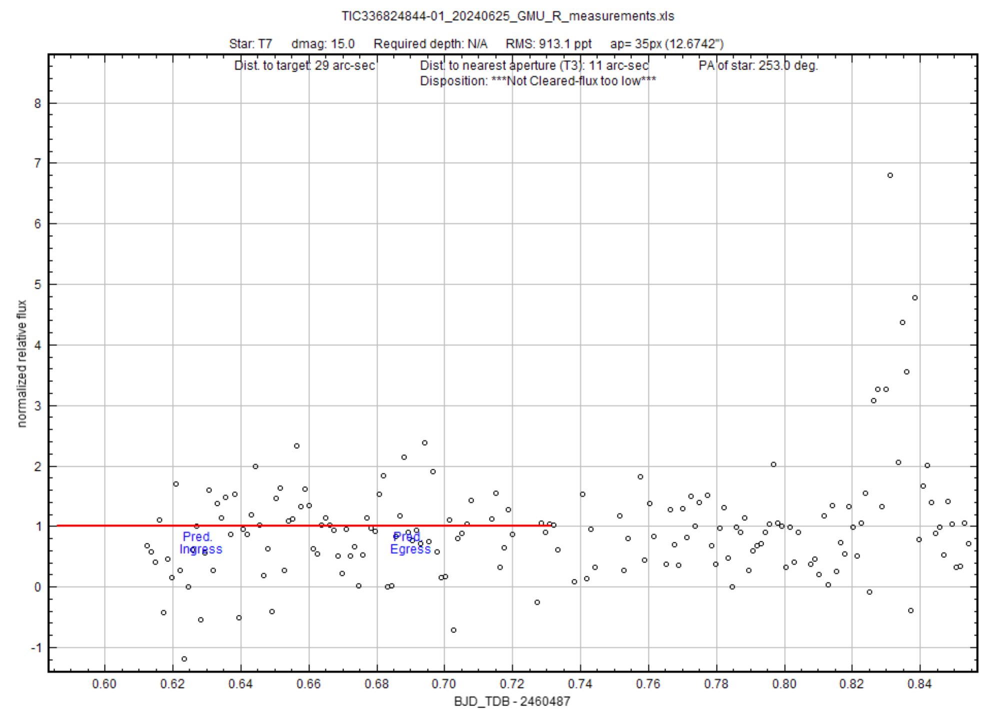


Figure 6. The Dmag vs RMS plot of TOI-3945.01. *Note.* The reference stars imported from the Gaia database are each indicated with a unique T number. T1 indicates our target star.



(a)



(b)

Figure 7. The light curves of stars T29 and T7. *Note.* (a) shows a disposition not cleared and (b) shows a disposition not cleared specifically due to low flux. The predicted ingress and egress times are 0.6279 BJD_{TDB} and 0.6896 BJD_{TDB}, respectively.

4. Discussion

In **Section 4.1**, we present our interpretation of our results. In **Section 4.2**, we place our results into context of the greater field of follow-up of candidate exoplanets from the NASA TESS mission.

4.1 Interpretation of TOI-3945.01's light curve and NEB results

In order to confidently determine the presence of a transit, there must be an apparent v-shaped profile in the light curve. In **Figure 5**, there seems to be no significant dip in the target's flux within the predicted ingress and egress times, but we must compare our light curve to the TESS light curve to check if the decrease in flux corresponds. The TESS light curve has an evident transit; however, it is worth noting that the light curve has a precise y-axis scale that increments by 0.005—refer to **Figure 1—**while that of our light curve increments by 0.1. Due to these scale differences, one of the slight flux dips in our light likely resembles the large dip in the light curve from TESS. We speculate that the midpoint of the transit occurs near 0.64 BJD_{TDB} with a depth of about 0.005, which may be strong evidence of a transit since our predicted transit depth, 0.0044, was not far off. Hence, this decline in flux may suggest the occurrence of a transit within the timeframe.

The dmagRMS plot—refer to **Figure 6**—does not signify any NEB signals as the RMS of all nearby stars are above the clearance NEB depth indicated by the green curve. **Figure 7** reveals the specific light curve for each star—stars T29 and T7 are shown in the figure—with a more detailed view of the NEB signals, but similarly, none of the nearby stars cleared the required NEB depth: all 216 stars were not cleared, where 138 of them were specifically due to low flux. Therefore, we have insufficient information to draw a comprehensive conclusion with the results from the NEB check—the nearby stars may or may have not interrupted with the signal.

4.2 Planet properties

Hot gas giants that have orbital periods less than 10 days are classified as hot Jupiters. Though they have similar size and mass as Jupiter, they tend to have significantly higher temperatures. If TOI-3945.01 is in fact an existing planet, then we suspect that it is a hot Jupiter since it has an orbital period of 4.46 days, which is less than 10 days. Moreover, it has an approximately equivalent size to Jupiter as disclosed by its planetary radius of 0.85622772±0.06538543 Jupiter radius. Lastly, with an equilibrium temperature of 830 K, it seems to be on the cooler side (below 973 K) of hot Jupiters[9]. In conclusion, these known traits reinforce our prediction that TOI-3945.01 is a hot Jupiter.

5. Conclusions & Future Works

Based on our results, our analysis of TOI-3945.01's light curve suggests its likelihood of being a real positive. Our light curve showed signs of a transit, but only exhibiting slight dips in flux of about 0.005. NEB analysis did not report any indication of eclipsing binaries near the target; hence, it is inconclusive whether or not NEB signals disrupted TESS's observation of the target. Lastly, while TOI-3945.01's identity is unknown, we expect the target to be a hot Jupiter with relatively cold temperature.

During the research, we have not performed any detailed statistical analysis of the light curve, leading to difficulties in drawing definitive statements. Furthermore, we are not exactly aware of the potential factors that may have affected our observation. Thus, future follow-up studies may complete this remaining part of the work, which will be essential to confirming the candidate's identity. In case the target is identified as a real positive, it may open up valuable opportunities for researchers to study the characteristics of hot Jupiter as they are rarely found in space. Ultimately, we believe TOI-3945.01 is a worthy candidate to invest more time and resources for additional investigation.

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