Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest TOI 3669.01

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Abstract

The Transiting Exoplanet Survey Satellite (TESS) mission gathers data for thousands of possible exoplanets and their host stars. This process happens by utilizing the transit photometry method, where any exoplanet candidates are marked as Objects of Interest and will be further analyzed using ground-based observation. This paper presents the ground-based observation and results of candidate exoplanet TOI (TESS Object of Interest) 3669.01, which revolves around the star TOI 3669. This study aims to further analyze if TOI 3669.01 is in fact an exoplanet. The raw telescope data was collected from the GMU Observatory. These images were taken, then reduced and plate solved using AstroImageJ and Alnitak Python code. AstroImageJ was utilized again to conduct multi-aperture photometry to generate a light curve to be further analyzed. Lastly, we conducted a NEB analysis on TOI 3669.01, which presented us with inconclusive results. Due to this reason and the transit not occurring during the expected times, we could not confirm the planetary nature of TOI 3669.01, and further research is needed to conclude its existence. However, we have evidence from previous research that could support the possible planetary nature of our target.

1. Introduction

Exoplanets are any planets outside of our solar system. After discovering the first exoplanet in the 1990s, studying exoplanets in astronomy has become increasingly important [6]. One of the most common ways to find an exoplanet is by utilizing the transit method, which was first successfully done in 1999 [6]. A transit happens when a planet passes between its star and the observer [12]. This causes a dimming in the light levels of the star, which can be shown on the light curve (graphs showing the light over time) as a dip in the brightness [12]. This light drop is crucial in determining if an exoplanet exists, but it can also reveal additional factors about the exoplanet. We can learn the exoplanet's orbital path and its size, as well as more information about the exoplanet's atmosphere, which ultimately reveals the planet's potential habitability. In order to find more exoplanets with this method, NASA launched the TESS mission– Transiting Exoplanet Survey Satellite. This mission was conducted to monitor the brightness of stars and for any drops throughout the sky. This data then goes through a ground-based follow-up observation to further verify and exoplanet or a false positive [11]. Candidate exoplanets are called TESS Objects of Interest (TOI).

Currently, thousands of candidate exoplanets have been found that need to be further validated [11]. The exoplanets validated through ground-based observation have compiled their research in the form of research papers. For example, Burt et al. studied TOI 1231 b, a Neptune-sized exoplanet orbiting star TOI 1231, to learn its radius, orbital period, and more about its atmosphere to label it as one of the coolest small planets accessible for atmospheric studies [1]. Another paper discussed TOI 778 b, a hot Jupiter orbiting dwarf star TOI 778 [2]. Although hundreds of candidate exoplanets have been verified, thousands still remain for further studies. This paper aims to aid in the gaps in knowledge of TOI 3669.01.

In this paper, we will observe and analyze the data to conduct a ground-based follow-up analysis of candidate exoplanet TOI 3669.01. The goal of the observations is to determine if a transit occurred during the expected time with the expected depth. TOI 3669.01 has some known characteristics, such as having an orbital period of 1.2126653 days and a radius of 10.81680 Earth radiuses [10].

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 3669.01 and our ground-based light curve analysis. In Section 4, we present our light curve results. In Section 5, we discuss our results. In Section 6, we present our conclusions and future work.

2. Observations

In Section 2.1, we present the TESS Object of Interest 3669.01 and its exoplanet candidate properties. We also present the candidate's host star's 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 TESS Input Catalog ID of our candidate exoplanet TOI 3669.01 is TIC 63470437, created in June 2021 and modified in July 2023 [9]. Our candidate exoplanet's RA and DEC coordinates are 02:06:24.57s and +33:51:22..66s, respectively [9]. This planet's transit midpoint is around 2459909.846648 BJD, and the orbital period is approximately 1.2126653 days [9]. The transit duration and depth are approximately 1.356 hours and 5132 ppm, respectively [9]. Finally, the planet radius, planet insolation, and planet equilibrium temperature are around 10.8168

R_Earth, 1112.72 Earth Flux, and 1609 K, respectively [9]. Additionally, TESS measured data from its host star, TOI 3669. The distance between Earth and the host star is 807.206 pc, the stellar effective temperature is around 5958.7 K, and the stellar radius is around 1.51 R_Sun [9].

Section 2.2

The TESS mission generated a light curve for TOI 3669.01, as shown in **Figure 1** [8]. This light curve shows our target's relative flux vs phase (hours). This light curve was found through the MAST Archive portal by entering the candidate exoplanet's name and downloading the TESS mission files given.

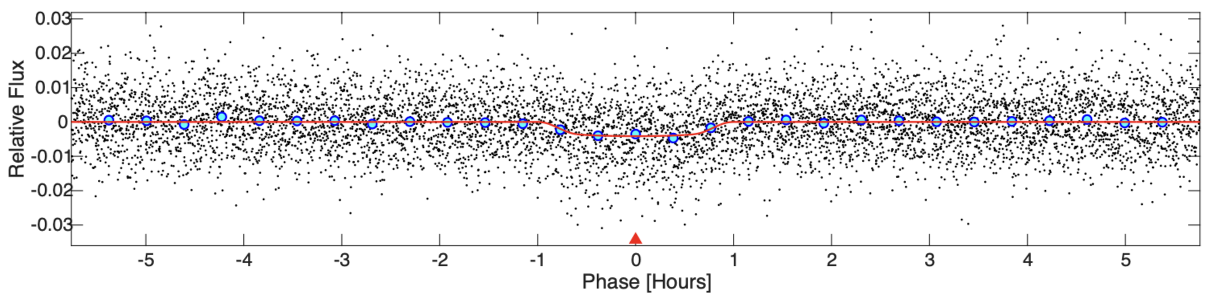

Figure 1: Light Curve plot of TOI 3669.01 from TESS summary report [8]

Section 2.3

This research paper uses data from the George Mason University (GMU) Observatory telescope using a red filter. On Wednesday, September 6, 2023, we observed 222 exposures, each with a 90-second exposure time. Further information can be referenced in **Section 2.1**.

3. Analysis

In Section 3.1, we present our data reduction process utilizing Alnitak Python code. In Section 3.2, we present our analysis of the ground-based light curve using AstroImageJ.

Section 3.1

To go through the data reduction process with the images of TOI 3669.01, Python was used to analyze the data. After collecting the exposures, we had to reduce and platesolve the images using Python code. To successfully do both procedures, we had to install Alnitak, the data reduction code. Alnitak also required the usage of several other Python packages: astropy, astroquery, photutils, numpy, scipyx, barycorrpy, and Matplotlib. Firstly, Alnitak reduces all the images, and any images that show streaking, blurriness, or displaced stars are outputted into a bad folder. All the good images will be plate solved and organized in a folder called reduced.

Section 3.2

We used AstroImageJ (AIJ) to continue the process and create our light curve. Utilizing the Aperture Photometry tool on AIJ, we generated a seeing profile for our target (**Figure 2**). The seeing profile shows us that our target has a photometry radius of 24, an inner annulus radius of 42, and an outer annulus radius of 62. To interpret this data, the light within the radius of 24 pixels primarily contains light from the star, while the annulus between 42 and 62 pixels is used to measure the light from the background. We then use the multi-aperture photometry tool on AIJ. Using the plate-solved sciences created using Alnitak, we add in the Gaia file containing TOI 3669.01s reference stars. Additionally, we chose at least ten reference stars with similar brightness and size of TOI 3669.01. **Figure 3** showcases the field image with apertures. After multi-aperture photometry was finished, we created a measurements table, which was then used to plot our light curve.

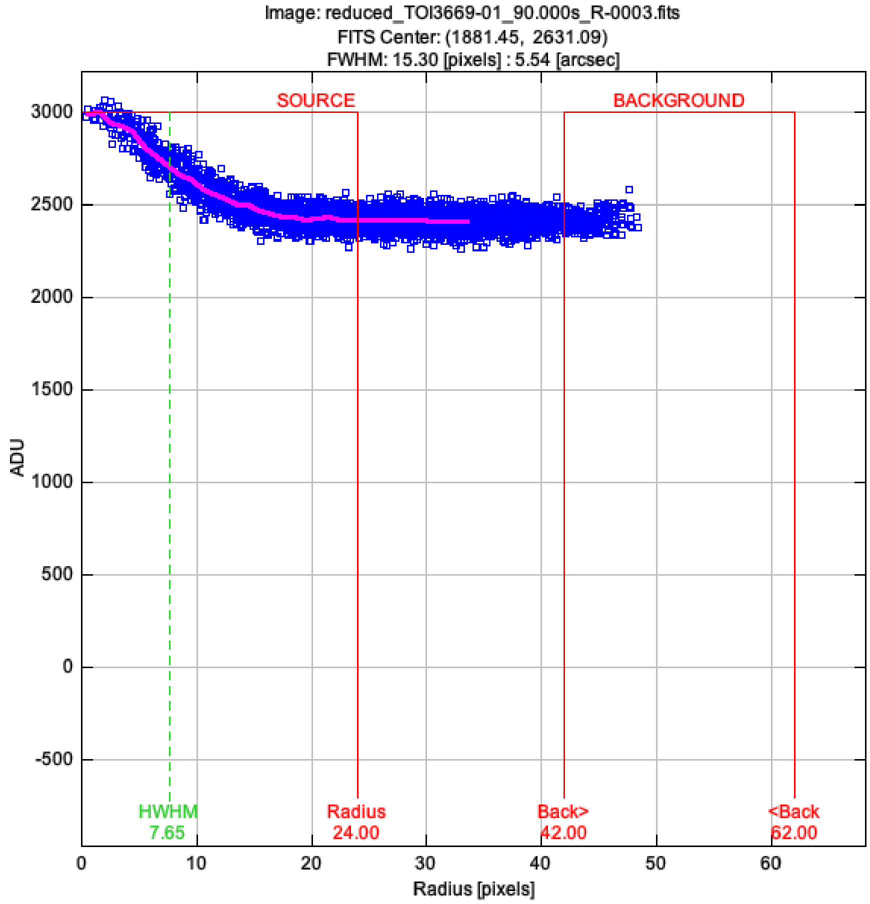

Figure 2: Seeing profile for TOI 3669.01. Note the photometry radius, inner annulus radius and outer annulus radius.

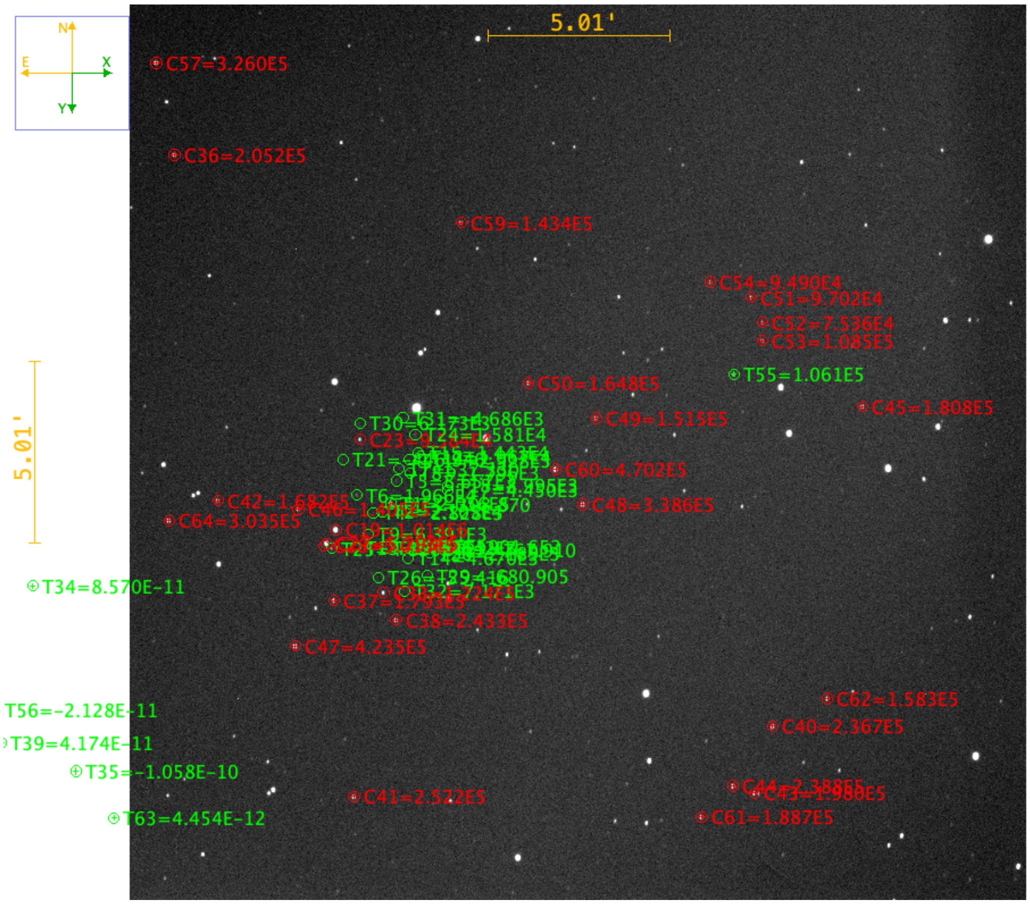

Figure 3: AIJ showcasing TOI 3669.01 and its reference stars.

To plot our light curve using AIJ, we first uploaded our measurement table previously saved and a plot configuration template. We then input the predicted ingress and egress times into the V. Marker 1 and V. Marker 2 boxes. The predicted ingress and egress times for TOI 3669.01 are 0.7894 and 0.8398, respectively. We then fixed up our light curve by appropriately adding the title and subtitle and selecting the necessary plots. We then reviewed each reference star previously selected, removing ones with significant plot variation. After we plotted our light curve, we examined and adjusted the shifting and scaling, utilizing the TFOP SG1 Guidelines for the correct information [3].

4. Results

In section 4, we present our light curve as well as other findings from our data analysis process.

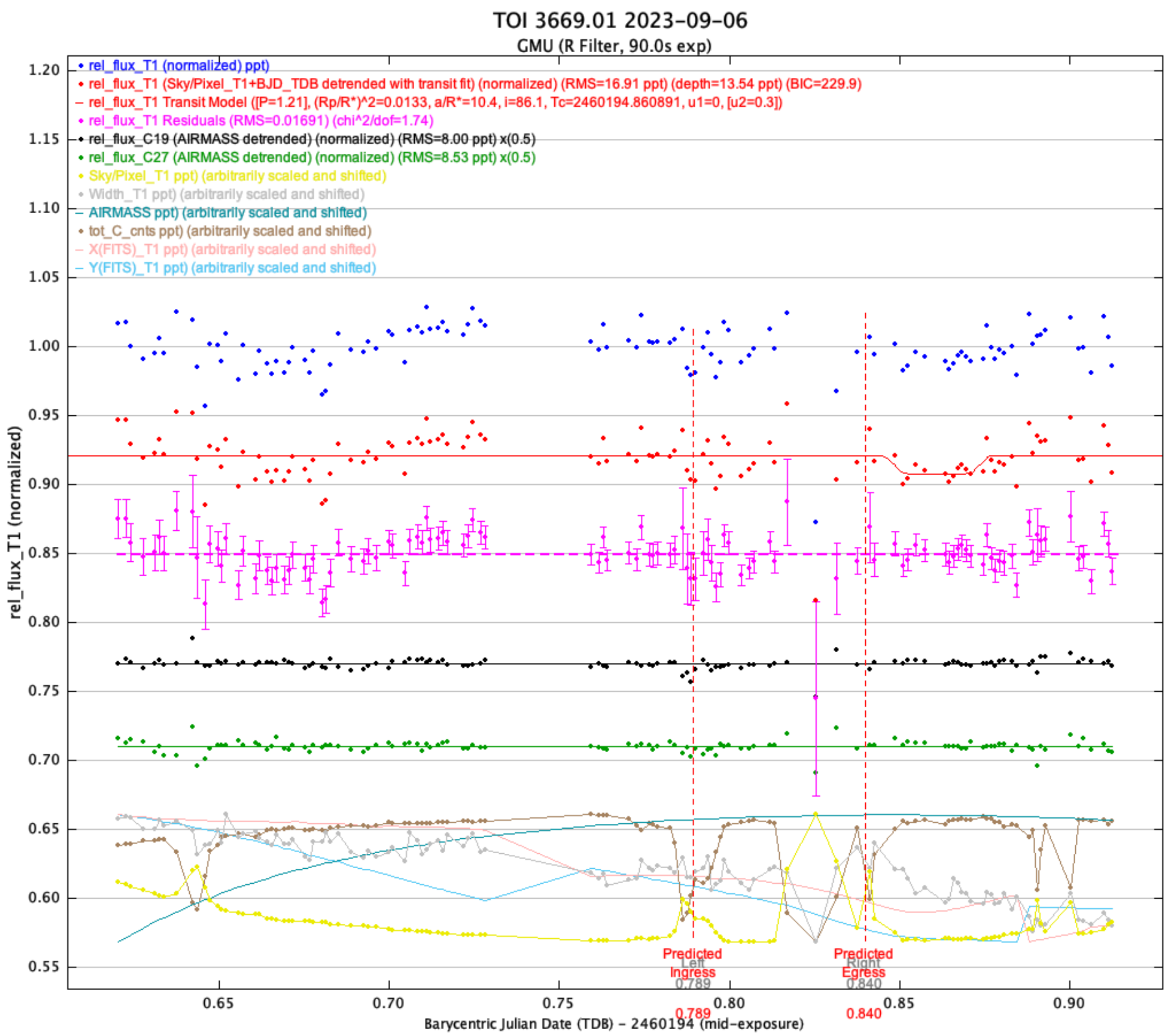

Figure 4: Plot of our Ground-Based Light Curve for TOI 3669.01 created on AIJ

The ground-based light curve (**Figure 4)** does not showcase a transit between the predicted ingress and egress times but instead showcases one outside the times. We have the plot of the normalized flux of T1 (TOI 3669.01). The data for two reference stars was also plotted to compare to our target.

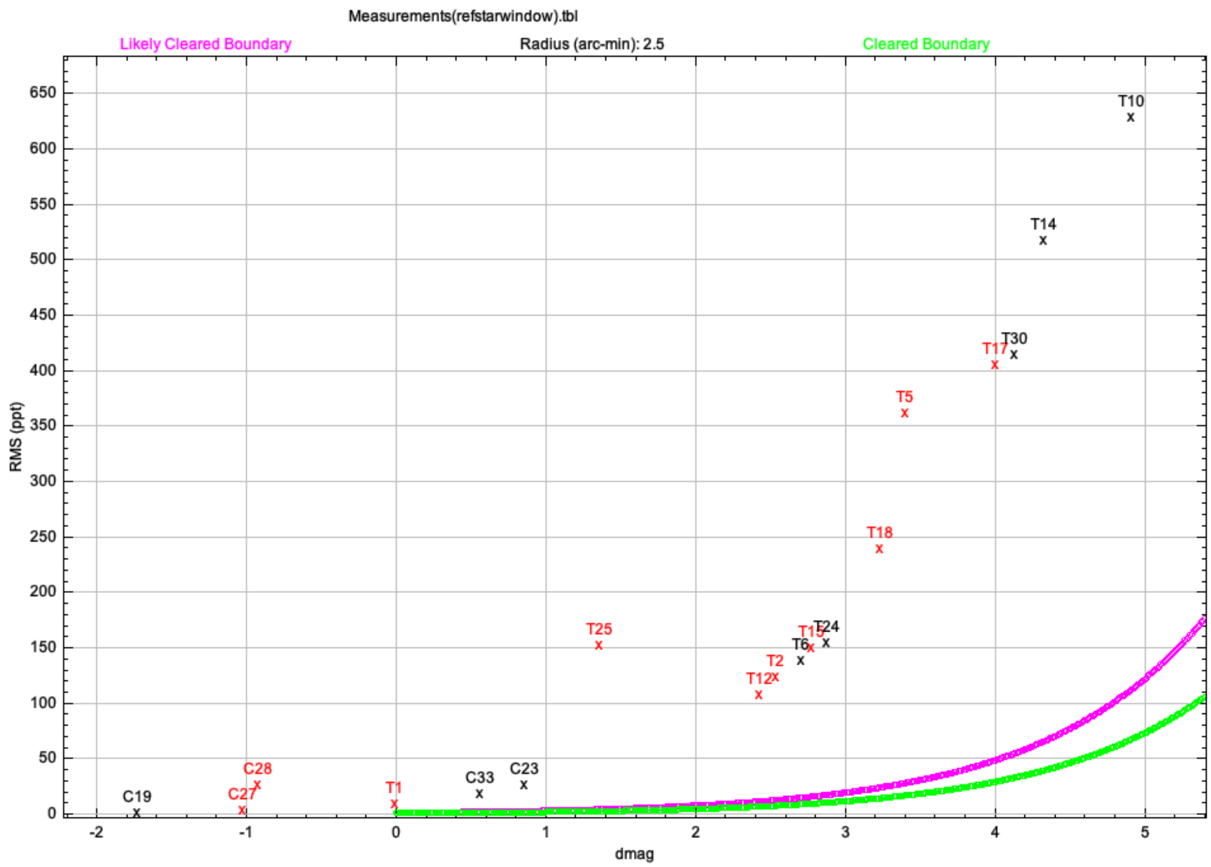

Figure 5: dmagRMS-plot of TOI 3669.01 and Gaia stars

Figure 5 showcases the boundaries for clearing the NEB check. All stars are above the lines.

5. Discussion

In Section 5.1 we present our interpretation of our results. In Section 5.2 we place our results into context of the greater field of follow-up of candidate exoplanets from the NASA TESS mission.

Section 5.1

It is inconclusive whether TOI 3669.01 is an exoplanet based on the data created and observed in this study. Further research is needed to conclude the target's identity. Referencing **Figure 4**, we can see that our light curve has a dip in its transit model outside of the predicted ingress and egress times. This could possibly be because of outdated ingress and egress times or transit timing uncertainties. Referring back to **Figure 4** again, we can notice the transit depth of this plot is 13.54 ppt. From the information found in the TESS Index Catalog, the transit depth was measured to be 5.132 ppt (5132 ppm); further information can be referenced in **Section 2.1**. The transit depth from this study is almost triple the one measured. This significant difference could be because of the scattering of data points and the relatively higher RMS value. This scattering and high transit depth could possibly be because of bad weather (i.e., cloud coverage) and background noise. Furthermore, referencing **Figure 5**, we can see in the dmagRMS-plot that none of the reference or target stars cleared the NEB check. The NEB check was inconclusive as no stars lay below the green/pink cleared boundary lines. This hints at TOI 3669.01 not being likely of an exoplanet, as the plot shows that the target could possibly be an NEB (Near Eclipsing Binary). Furthermore, we can not prove that the transit in the light curve is that of an exoplanet, as it could be of an NEB. However, utilizing data for TOI 3669.01 found on the Exoplanet Follow-Up Observing Program (ExoFOP), we were able to gather more evidence on our target that can potentially prove it being an exoplanet.

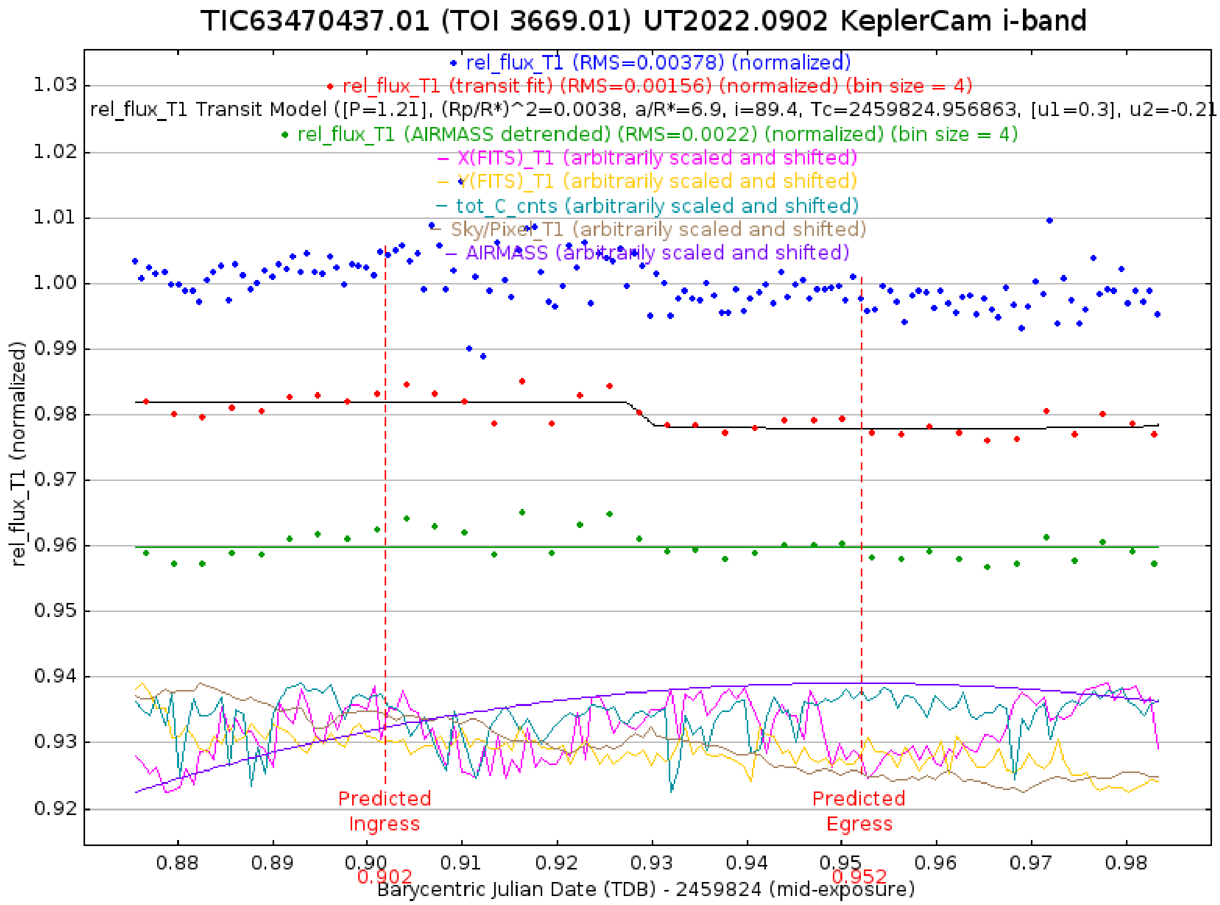

Figure 6: Light Curve of TOI 3669.01 from September 2, 2022

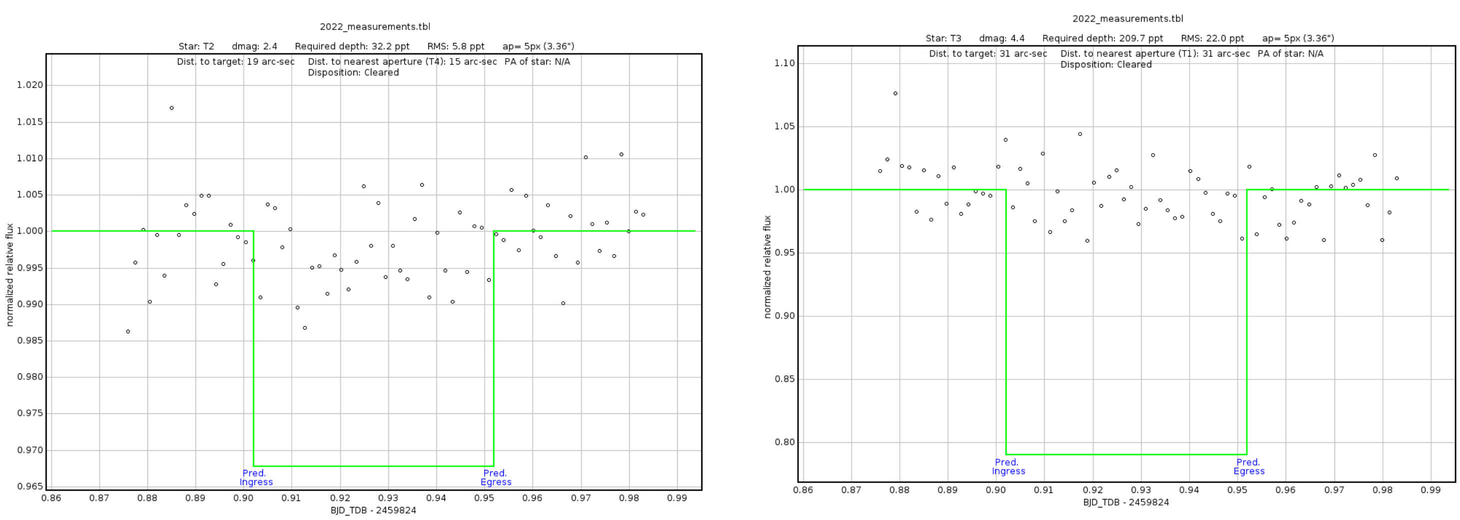

Figure 7: NEB Checks of Nearby Stars T2 and T3 from 2022

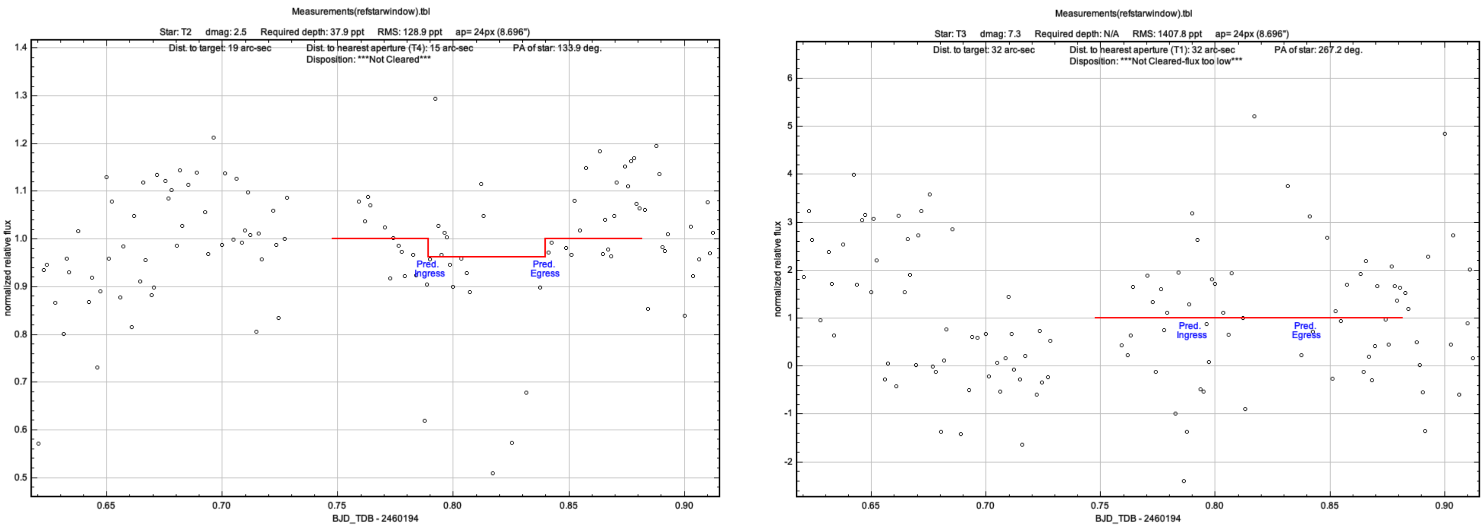

Figure 8: NEB Checks of Nearby stars T2 and T3 from 2024 (this data)

Referencing **Figure 6**, a light curve of TOI 3669.01 found on ExoFOP, we can see the dip in the data between the predicted ingress and egress times [5]. To further back up the possibility that TOI 3669.01 can be an exoplanet, and that the light curve shows a transit from an exoplanet and not an NEB, we can compare the NEB checks for reference stars T2 and T3 from 2022 (the same year as the light curve in **Figure 6**) with 2024 (our data). Referencing **Figure 7** and **Figure 8**, showcasing NEB checks for T2 and T3 from 2022 and 2024, respectively, we can see that the 2022 NEB checks were cleared while the 2024 NEB checks were not cleared [5]. While the dmagRMS-plot reached the same conclusion as **Figure 8**, leading us to possibly believe the target may be an NEB, analyzing **Figure 7** with the cleared NEB plot can help us realize the possibility of TOI 3669.01 being an exoplanet and not a NEB. Overall, while our data may have given us inconclusive results with an unclear understanding of TOI 3669.01 being an exoplanet, referencing other data gave us more evidence to further prove the possibility that our target may indeed be an exoplanet. Further analysis will be needed to conclude its status.

Section 5.2

The temperature of TOI 3669.01 (1609 K) indicates that our target could potentially be a hot Jupiter. Hot Jupiters tend to have a temperature between 1300 to 3100 Fahrenheit [4]. This temperature converted to Kelvin is between ~978 K and ~1978 K, which our target falls in between. While there may not be more published research on our target, research has been published on other hot Jupiters discovered through the TESS mission. TOI 2046b, TOI 1181b, and TOI 1516b are all hot Jupiters found by the TESS mission [7]. Petr Kabáth et al. also found the orbital periods for these three exoplanets, which were between 1.4 and 2.05 days [7]. The orbital period for TOI 3669.01(a potential hot Jupiter) was ~1.2 days, similar to the proven hot Jupiters' orbital periods. Furthermore, the light curves for the three systems were generated using Single Aperture Photometry (SAP), while the light curve for TOI 3669.01 was generated using the multi-aperture photometry tool on AIJ: both utilized aperture photometry [7].

6. Conclusions and Future Works

From our results and discussions, we were not able to determine the planetary nature of our target. We analyzed the light curve, NEB plot, and the dmagRMS-plot. The light curve had a transit that was not between the predicted ingress and egress times. None of the NEB checks were cleared, either. Although the results were inconclusive, we could use evidence from previous research to back up the possibility that our target could potentially be an exoplanet and not a NEB.

For a further understanding of TOI 3669.01, other researchers should observe and collect more data. For one, more research should be done to reach a definite conclusion on the planetary state of this candidate. If this candidate is indeed an exoplanet, statistical false-positive validation should be done to validate the state of this exoplanet. Afterward, TOI 3669.01 should be further studied to research its characteristics, such as confirming the target's type with other research as well. To sum up, TOI 3669.01 proves to be a compelling candidate for research, and we hope this study and analysis prove fruitful for future research.

7. References

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