Ground-Based Light Curve Follow-Up Validation Observations of TESS Object of Interest 3777.01

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Abstract

The TESS (Transiting Exoplanet Survey Satellite) was launched to search for new exoplanet candidates (1). One such candidate found by the TESS was TOI 3777.01 around host star TOI 3777. This paper aims to confirm the identity of TOI 3777.01 as an exoplanet. To reach these goals, we plated-solved images of TOI 3777 taken by George Mason University's ground-based telescope using tools from the Python programming language. We then applied the software AstroImageJ to generate a flux light curve and perform an NEB (Nearby Eclipsing Binary) check of TOI 3777 using these plate-solved images. We were able to confirm that a change in luminosity on our flux light curve occurred but could not rule out the possibility of an NEB or other false positive causing the event.

1. Introduction

One of humanity's oldest and greatest unsolved questions is whether life exists on other planets besides Earth (2). Studies that attempt to answer this topic are focused on exoplanets, which are planets that orbit around a star besides the Sun. When exoplanets pass between their host star and Earth, we can observe a decrease in the luminous flux of the star, which is called a planetary transit. Due to the periodic nature of a planet's orbit, planetary transits occur regularly and are predictable (1).

The TESS (Transiting Exoplanet Survey Satellite) was launched in 2018 to use this planetary transit method to observe at least 200,000 dwarf stars due to their abundance and highest probability of having an Earth-like habitable exoplanet.[1] Raw data from the TESS Mission is sent to NASA's Mission Operations Center, processed by its Payload Operations Center, and further analyzed by the Science Processing and Operations Center, which produces light curves and checks for planetary transits. The TESS Science Office takes this information to produce a list of TESS Objects of Interest (TOI) (3).

However, these exoplanet candidates need follow-up observations from ground-based observatories to verify their existence and identity. As of August 2nd, 2024, 543 out of 7204 TESS candidates have been verified as exoplanets (4). An example is the identification of a mini-Neptune and a super-Earth around host star TOI 836 (5). No such publication has yet been conducted for TOI 3777.01.

This paper will present follow-up observations of TOI 3777.01. TOI 3777.01 has an $R_{\oplus}$ of 9.5, an orbital period of 2.34 days, a transit duration of 2.53 hours, and a transit depth of 4580 ppt (6). Our goal is to confirm that a transit did occur at TOI 3777.01 with the aforementioned characteristics.

In section 2, we will share our observations from TESS and the George Mason University 0.8m telescope. In section 3, we will share our analysis of the TESS light curve for TOI 3777.01 and our ground-based light curve analysis. In section 4, we will share our light curve results. In section 5, we will discuss our results. In section 6, we will share our conclusions and future work.

2. Observations

In section 2.1, we present TOI 3777.01 and its characteristics as an exoplanet candidate, a as well as the properties of its host star TOI 3777 from the TESS Input Catalog and other archival sources. In section 2.2, we present the observational data gathered from the George Mason University 0.8m telescope.

2.1 TESS Observations

The TESS mission identified TOI 3777.01 as an exoplanet candidate in the year 2021. It's host star, TOI 3777, has a stellar radius of 1.41467, a stellar effective temperature of 6545.0 (K), a stellar mass of 1.35, right ascension (RA) of 8:27:16.49, and a declination (DEC) of +50:45:28.20 (6). TOI 3777.01 has a planet radius of 9.5 ($R_\oplus$), an equilibrium temperature of 1738 (K), an orbital period of 2.34 days, a transit duration of 2.53 hours, and a transit depth of 4580 ppt (6).

2.2 Ground Observatory Observations

On the night of February 6th, 2024, we used the George Mason University (GMU) 0.8m telescope to observe TOI 3777.01 with an R filter. We took 189 exposures starting from 6:35 pm EST to 6:10 am EST the next day. Each exposure time was 85 seconds long. The predicted ingress time was at 10:16 pm EST and the predicted egress time was 12:47 am EST the next morning (10).

3. Analysis

In section 3.1, we present the tools we used to data-reduce and plate-solve the raw images of TOI 3777.01 taken by GMU's 0.8m telescope. In section 3.2, we present the generation and analysis of a light curve from these reduced and plate-solved sciences using AstroImageJ (AIJ).

3.1 Plate-Solving and Data-Reducing

First, we visually examined each of the raw sciences for complications such as streaking, shifting, blurring or other issues, and separated problematic exposures from the other science images. An example of a science that had to be removed is shown in Figure 1, and a suitable science is shown in Figure 2. Then, we used Alnitak, a python code that plate-solves and reduces images through nova.astrometry.net. (7). Using the pip package management system, we then installed Alnitak's dependencies: the astropy, astroquery, photoutils, numpy, scipyx, barycorrpy, and matplotlib Python packages. Using a command line, we ran Alnitak with a generated API key from nova.astrometry.net to plate-solve and reduce the exposures using the science-dark, flat-dark, and flat images also taken by the GMU 0.8m telescope. More information on this process can be found in the "SCHAR Campus Telescope Data Analysis w/ alnitak Tutorial v2021" (8).

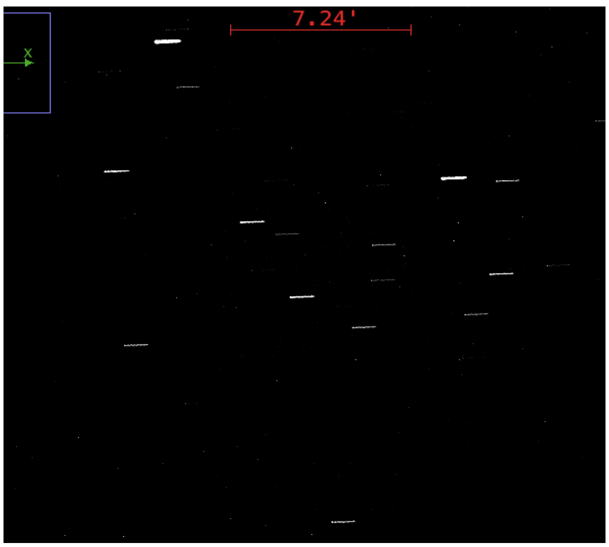

Figure 1: Raw science image of TOI 3777.01 removed due to streaking

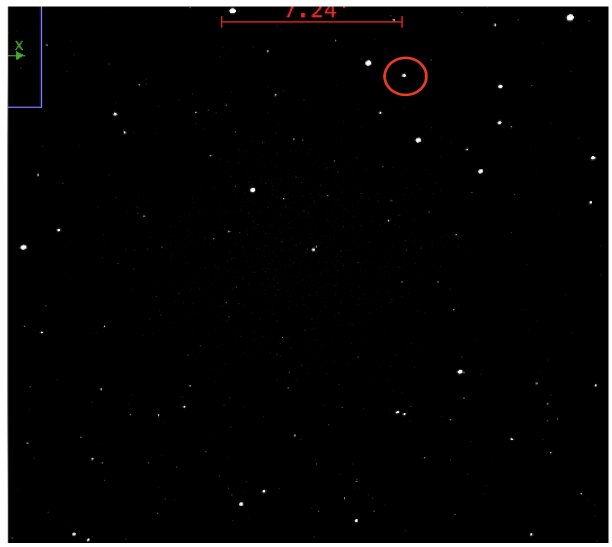

Figure 2: Acceptable raw science image of TOI 3777.01 (circled in red)

3.2 Light Curve Generation and Analysis with AIJ

We uploaded our plate-solved and reduced images to AIJ's image viewer and aligned them using the stack aligner. We then used the Aperture Photometry Tool to generate a seeing profile of TOI 3777. Next, we performed multi-aperture photometry using a Gaia reference star file for TOI 3777 to generate a flux light curve. We entered information about the host star including its period and stellar radius into the " Data Set 2 Fit Settings" window, and plotted Sky/Pixel_T1, Width_T1, AIRMASS, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1). We removed several comparison stars with excessive scattering and variation of flux. We then plotted the delta-magnitude (of flux) against the RMS for each star to check for Nearby Eclipsing Binaries (NEB). More details of this procedure can be found in the "Campus Telescope TESS Follow-Up Light Curve Tutorial - Schar Program" (9).

4. Results

In Figure 3, we present our extracted ground-based light curve of TOI 3777. In Figure 4, we present the delta-magnitude vs RMS graph generated from our light curve.

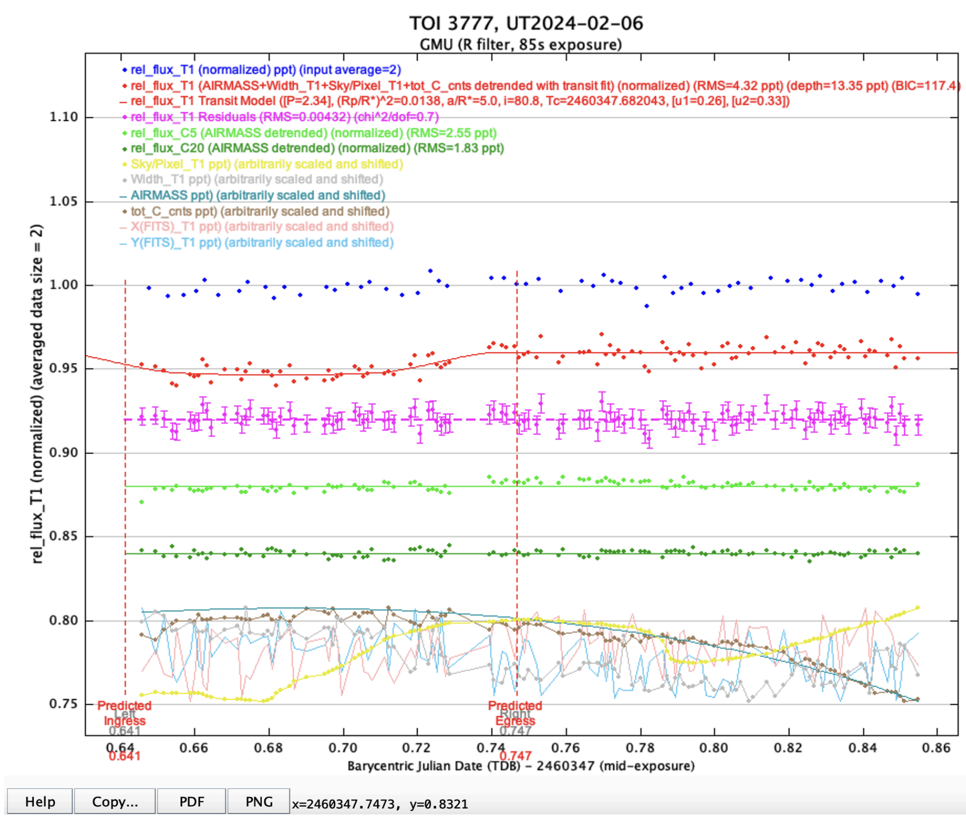

Figure 3: Generated ground-based flux light curve of TOI 3777

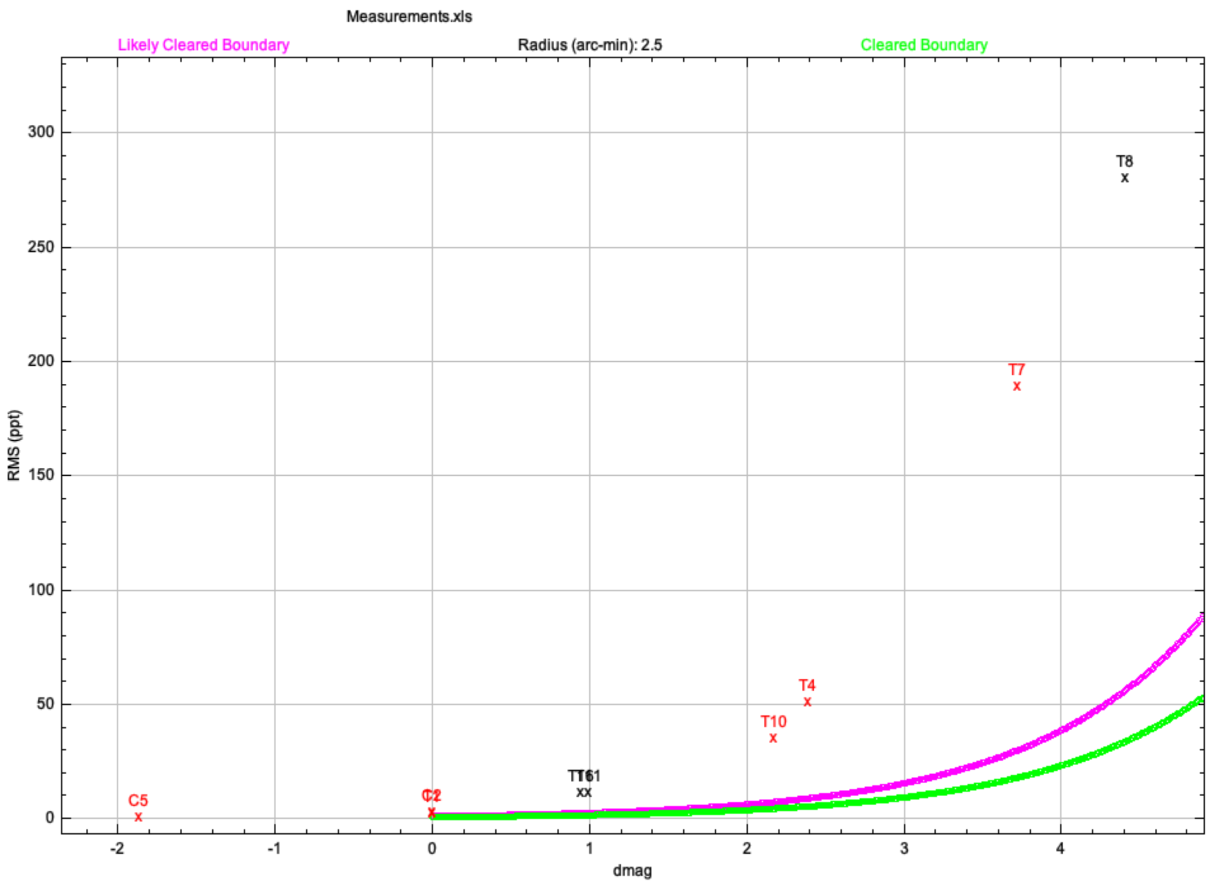

Figure 4: Delta-Magnitude vs RMS graph

5. Discussion

There is a definite dip in the flux of TOI 3777 as shown in the light curve on Figure 3 that matches the predicted ingress and egress times (10). Although the 13.1 ppt depth in our light curve is much greater than the 4.1 ppt predicted transit depth, this could be due to the 4.32 ppt RMS. In addition, the relatively low scattering means that there is not enough noise to invalidate the transit. We also performed an NEB check as shown in Figure 4, but none of the stars were cleared as not being an NEB. However, none of the comparison stars were plotted in the upper left quadrant of that graph, and all still formed a curvature, so it is unlikely that any of them are a

NEB. However, we could not rule out other false positives that require further work to investigate.

6. Conclusion and Future Work

The ground-based light curve has sufficiently little noise indicating that an event occurred on TOI 3777. We were able to remove the possibility of nearby stars being an NEB. Although it is probable that TOI 3777.01 is a transiting exoplanet, we were not able to disprove all feasible false-positives.

More future work is needed. We could use Vespa, a Python code, to calculate the probability of a false-positive for our transit signal (11). In addition, we could use the radial-velocity method to more rigorously confirm that there is no NEB around TOI 3777 and get a more accurate value of the mass and density of TOI 3777.01. Finally, we could perform high-contrast imaging to find faint, nearby stars. All of these methods will help prove whether TOI 3777.01 is an exoplanet.

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