Ground-based light curve follow-up validation observations of TESS object of interest TOI 3873.01

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ABSTRACT

The Transiting Exoplanet Survey Satellite (TESS) has discovered 7,846 possible exoplanet candidates using the transit method as of 2024-07-23, but only 543 have been confirmed by ground-based follow-up observations (IPAC, 2024). In this paper, we present the follow-up validation observations and analysis of candidate TOI-3873.01 by the George Mason University 0.8m telescope. The goal of this paper is to confirm the planetary nature of TOI-3873.01 and to disprove the possibility of the transit signal being detected by a false positive (possible NEB). 156 total science exposures were taken of the target. They were data reduced, plate solved, and aligned using AstroImageJ. Multi-aperture photometry was then performed to produce a light curve. The results of the light curve provide evidence towards there being an actual transit. We are able to confirm the probable planetary nature of TOI-3873.01. A NEB check was done through AstroImageJ, though the results are inconclusive. Because of this, we are not able to prove whether or not these results are caused by a false positive due to an NEB. Future research and observations must be done to confirm the event that TOI-3873.01 is a real exoplanet. Further tests and analyses can be performed to then conclude important factors about the atmosphere and possible habitability of TOI-3873.01.

INTRODUCTION

An exoplanet is any planet, rogue or orbiting another star, beyond our solar system (*What is an Exoplanet?*, n.d.). Since the first confirmed exoplanet in the 1990s, astronomers have developed new technologies, such as better ground-based and orbiting telescopes, to more effectively locate and study these exoplanets (*In Depth: Exoplanets*, n.d.). The main goal of this search for exoplanets is to find signs of habitability and life beyond Earth, as well as gaining a better understanding of the universe as we know it (*Why We Search*, n.d.). While there are several methods of finding exoplanets, the most common is the transit method in which transits - when a planet passes in between a star and its observer - are detected from a certain star. They are detected as repeated small dimmings in the light from the star, caused by the proposed exoplanet blocking some of the star's light from our perspective (*What's a Transit?*, n.d.).

The Transiting Exoplanet Survey Satellite (TESS) is a NASA mission launched in 2018 designed specifically to find exoplanets that may be capable of hosting life using the transit method (*Mission Overview*, n.d.). Over the course of its mission, TESS uses its 4 cameras to capture 2-minute exposures of 200,000 of the brightest stars, and 30-minute exposures of every visible star. Machine learning is then used to analyze the light curves of each star to propose exoplanet candidates.

Follow-up validation observations performed by ground-based astronomers must be done following the discovery of the exoplanet candidates by TESS, in order to prove their existence and to rule out the possibility of there being a false positive (*TESS*, n.d.). False positives are commonly caused by a nearby eclipsing binary (NEB), so checks for those will be a necessary part of the follow-up validation process (Leuquire et al. 2018). A study by Clark et al. (2023), performed follow-up validation observations of a TESS object of interest (TOI) with the use of light curve analyses and radial velocity measurements to confirm the presence of a hot Jupiter, TOI-778 b, orbiting a F3V-dwarf star, TOI-778. Another study by Deeg et al. (2023), performed follow-up validation observations of a TOI using radial velocity measurements to confirm the presence of the hot super-Earth-like planet, TOI-1416 b, orbiting an early K-type dwarf star, TOI-1416. Thousands of exoplanets still need to be confirmed through this process (IPAC, 2024). While there have been previous follow-up validation observations of TOI-3873.01 by TFOPWG, there have been no papers published about the candidate.

In this paper, we present follow-up validation observations on TOI-3873.01, (TIC 154126149.01). It has a radius (R_Earth) of 14.6884, an orbital period (days) of 3.895, and it orbits a sun-like F-type star, TOI-3873 (EXOFOP, 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.

In Section 2, we present our observations from TESS, TFOPWG, and the George Mason University's 0.8m telescope. In Section 3, we present our analysis of the TESS light curve for TOI-3873.01 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.

OBSERVATIONS

2.

In Section 2.1, we present the TESS object of interest TOI-3873.01 and its candidate properties, and host star's properties obtained from the TESS Input Catalog, and NASA exoplanet archive. In Section 2.2, we present previous follow-up validation observations done by TFOPWG.

In Section 2.3, we present an overview of the observational data collected, and methods utilized by George Mason University's 0.8m telescope.

2.1.

A new potential exoplanet candidate was observed by TESS in 2021 while observing the Sun-like star TOI-3873. This star has a right ascension (RA) of 14h09m58.45s and declination of (DEC) of +70h03m55.87s, a stellar effective temperature (K) of 6071, a stellar radius of ~1.479, and stellar mass of 1.13.

The aforementioned potential exoplanet candidate, named TOI-3873.01, has a planet radius (R_Earth) of ~14.688 , a planet equilibrium temperature (K) of 1114, an orbital period (days) of ~3.895, a planet transit duration (hours) of ~1.386, and a transit depth (ppm) of 8970.
(IPAC, 2023).

2.2.

Allyson Bieryla, from the group: TFOPWG, used the KeplerCam to make observations of TOI-3873.01 (EXOFOP, 2022).

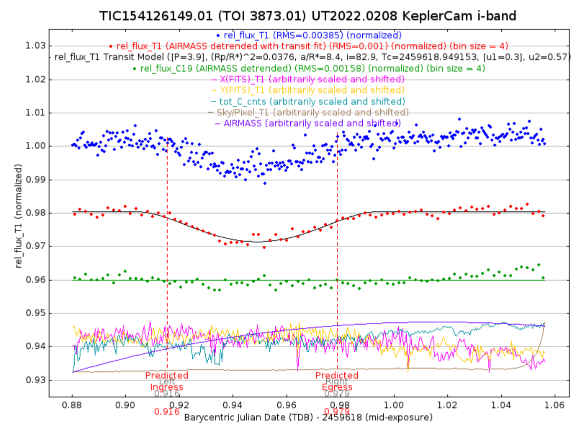

Figure 1: Light Curve of TOI-3873.01, taken by KeplerCam (i-band) 2022-02-08.

2.3.

George Mason University (GMU) performed follow-up observations of the candidate TOI-3873.01 on 2024-06-21 to help verify its existence. This started at 21:50 and went until 04:32 (EST). A total of 156 total science exposures were taken with an exposure time of 90s, and an R filter. However, due to streaking and the target being out of frame in some images, only 152 exposures ended up being used. 20 dark images and 10 flat images were taken from the follow-up observation of TOI-3945.01 done on 2024-06-25 by GMU, as none were taken during the observations of TOI-3873.01. This was fine to do as the exposure times matched up. 10 of the dark images were collected with 3s exposure times, matching the flat images, and the other 10 dark images were collected with 90s exposure times matching the science images.

ANALYSIS

3.

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

3.1.

We used AstroImageJ, as well as information from the NASA Exoplanet Archive and EXOFOP to complete the Analysis on TOI-3873.01. Using the RA (14h09m58.45s) and DEC (+70h03m55.87s) coordinates, we were able to locate the target star, and keep it in frame while the science exposures were taken. Before we could plate-solve our images, we first had to data-reduce them to reduce the amount of noise captured in the background of these images. We used the AstroImageJ CCP Data Processor to do this. We performed dark subtraction and flat division to produce more visible and usable images. Automatic plate-solving, using astrometry.net (*Astromtery.net*, n.d.) and AstroImageJ, was then done to determine the location in space where our images were taken. This is important as reference stars must be chosen and their location in comparison to the target star must be known for proper and automatic alignment. We then aligned our images using AstroImageJ. An example plate-solved science image in Figure 2.

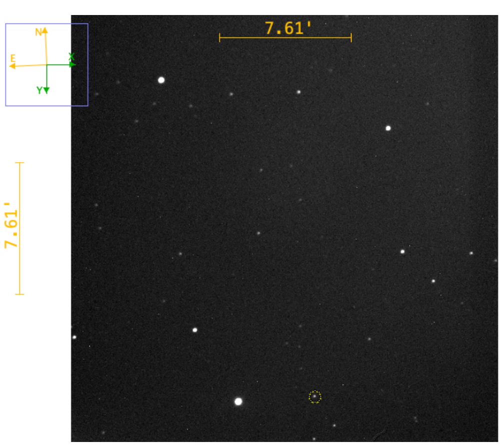

Figure 2: Example plate-solved science image with target TOI-3873 circled at the bottom.

A seeing profile was made using a virtual stack of all the aligned science images. It was made to find the target's pixel radius (aperture size), as well as the inner radius and outer radius (annulus sizes) The seeing profile made as shown in Figure 3.

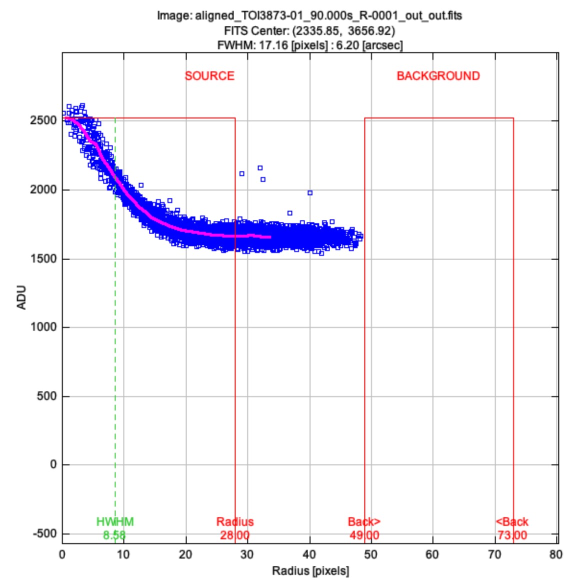

Figure 3: Seeing profile of TOI-3873, with radius of 28.00, inner radius of 49.00, and outer radius of 73.00.

We then placed a temporary 2.5' circle around the target, as we needed to find all viable reference stars nearby to TOI-3873. They could be the cause of a NEB as discussed in the Introduction. 8 Gaia star apertures that were within the 2.5' circle were then downloaded (https://www.astro.louisville.edu/cgi-bin/gaia_to_aij/upload_request.cgi?ra=14:09:58.528&dec=+70:03:55.75&date_obs=2024-07-29&mag=12.6262&depth=8.97) and placed onto the stack. 10 other reference stars were selected manually, and their apertures were placed onto the stack. Multi-Aperture Photometry was then performed to generate a light curve and measurement table for TOI-3873.

3.2.
In order to accurately interpret the results of our analysis and light curve, we must first change many of the settings that affect the appearance and accuracy of our light curve. We first uploaded a default template for our light curve (Conti, n.d.). In the “Multi-plot Main” window we added/adjusted: the predicted ingress (0.6513) and egress (0.7093) of the transit, title, and X and Y axis titles and ranges. Multi-plot Main Window as shown in Figure 4.

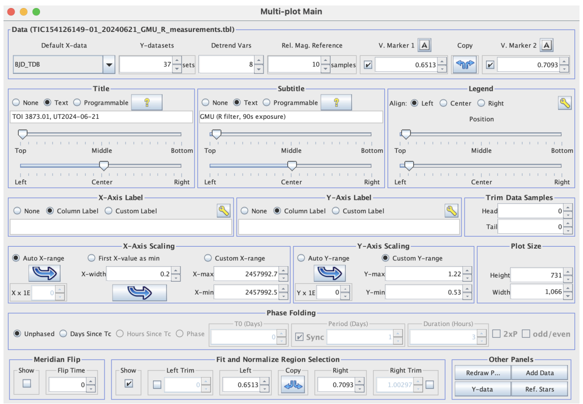

Figure 4: Final “Multi-plot Main” window for TOI-3873.

In the “Data Set 2 Fit Settings” window, we entered orbital, stellar, and transit information obtained from the NASA Exoplanet Archive as well as EXOFOP. The Linear LD u1 and Quad LD u2 values were taken and entered from (Eastman et al. 2013).
In the “Multi-plot Y-data” window, we checked our reference stars for major variability and change in how well the model of the transit matched the light curve. Reference stars: C2, C3, C5, C6, C10, C12, C13, C14, and C17, were all then subsequently unchecked from “Multi-plot Reference Star Settings”. “Multi-plot Reference Star Settings” as shown in Figure 5.

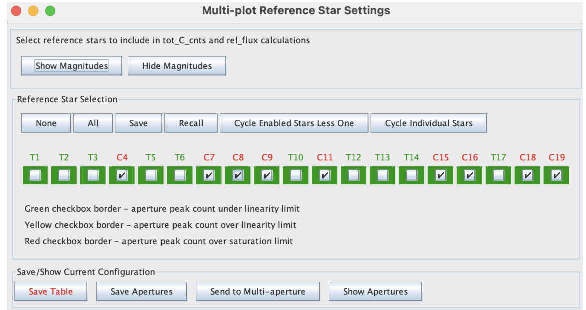

Figure 5: Final “Multi-plot Reference Star Settings” window.

Detrending Parameters: AIRMASS, Sky/Pixel_T1, Width_T1, tot_C_cnts, X(FITS)_T1, Y(FITS)_T1, were then plotted and shifted using the information provided by the TFOP SG1 Observation Guidelines (Conti, 2020). Reference Stars C4, and C8 were then both plotted and shifted, then detrended with AIRMASS. This was to help show a reference for how stars with no expected transit compare to the target. The target light curve was then detrended with Width_T1, Sky/Pixel_T1, X(FITS)_T1, as these resulted in the lowest RMS value for the target light curve. Finally a NEB check was performed.

RESULTS

4.
In Section 4.1, we present the results from the light curve analysis. In Section 4.2, we present the results from the NEB check.

4.1.

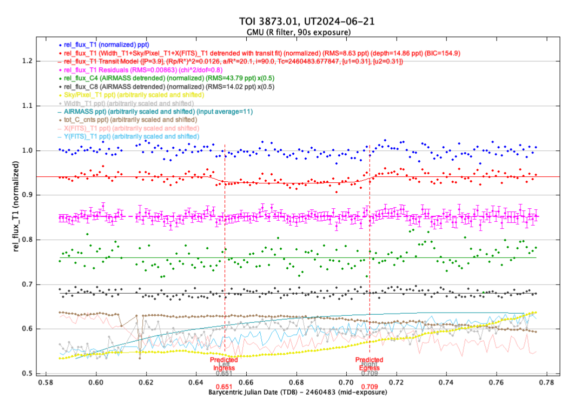

Figure 5: Final light curve of TOI-3873.

Figure 6: Final "Data Set 2 Fit Settings" window.

As shown in Figure 5, there appears to be a slight dip in the light curve alluding to a possible transit. The predicted ingress and egress values also match up with the actual observed ingress and egress values as shown by the vertical red dashed lines (predicted ingress/egress) covering the vertical gray dashed lines (observed ingress/egress) completely.

As shown in Figure 6, from our light curve, we calculate a transit depth (ppt) of 14.86, and a transit duration (hms) of 01:38:57. An RMS value (ppt) of ~8.628 , chi^2 value of ~114.662, degrees of freedom (dof) equal to 144, and other statistical values can also be collected.

4.2.

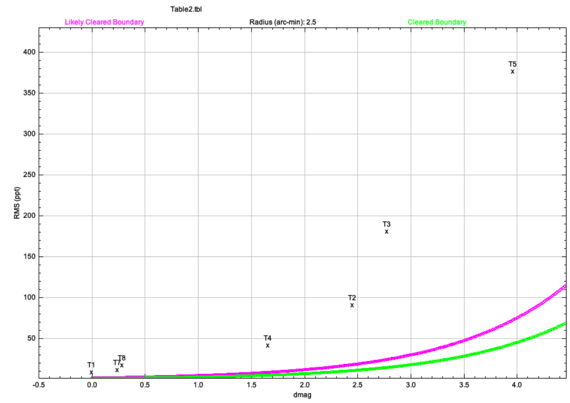

Figure 7: dmagRMS-plot for NEB check

Figure 7 is the dmagRMS-plot automatically created after the NEB check completed. This will be used to conclude whether there is a NEB system that may be resulting in a false positive transit signal from TOI-3873.

DISCUSSION

5.

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.

5.1.

Based on the results of our observations and analysis, we have evidence of an exoplanet transit around TOI-3873. As stated in Section 4.1, we see a dip in light curve, and the predicted ingress and egress match the observed ingress and egress. The observed transit duration (hms) of 01:38:57 differs moderately from the expected transit duration (hms) of 01:23:10 ± 00:18:11. It's important to note however that the observed transit duration (01:38:57) falls into the predicted possible transit duration range (00:64:59, 01:41:21). The observed transit depth (ppt) of 14.86 is slightly larger than the predicted transit depth (mmag) of ~9.78 (EXOFOP, 2023). We will assume 1 ppt = 1 mmag, due to this relatively shallow transit depth (Conti, 2020). As stated in section 4.1, the chi^2 value of ~114.662 with dof of 144 provide further evidence to this conclusion, as performing a chi^2 goodness of fit (GOF) test results in a p-value of 0.9658. Using a standard significance level of 0.05 and a null hypothesis stating there is no significant difference between the observed and expected data, we cannot reject this null hypothesis. There is no significant evidence of a difference between the observed and expected data. This means our observed light curve is very similar to the expected light curve from the TESS mission.

We have not yet concluded if this was caused by a false positive. As seen in Figure 7, none of the reference stars are below both the purple and green “cleared” lines. This means none of the reference stars used pass the NEB check. None of them appear as outliers so the results of this check are inconclusive. We are unable to confirm that there are no NEBs, however there are no obvious NEB candidates among the reference stars selected.

5.2.

Referring to Section 2.1, TOI-3873.01 has a predicted radius (R_Earth) of ~14.688, this is equivalent to a radius (km) of ~93,684. Jupiter has a radius (km) or ~71492 (Barnett, 2024). This would make TOI-3873.01 about 1.3x the size of Jupiter. Although the orbital period of TOI-3873.01 is only 3.9 days, suggesting it may be a Hot Jupiter (Wang, n.d.), its equilibrium temperature (K) of 1114 is significantly less than expected Hot Jupiter temperatures (Baxter et al. 2020). A similar exoplanet validation paper was published by Galazutdinov et al. (2023), where TOI-1408 b, was discovered to have a mass (M_Jup) of ~1.69 (Galazutdinov et al. 2023).

CONCLUSIONS AND FUTURE WORK 6.

Based on our results and discussion, we conclude that TOI-3873.01 has evidence that supports it being a valid exoplanet. From our light curve we were able to detect a transit signal similar to that predicted by TESS. We are able to predict a possible classification of TOI-3873.01 as a cooler Hot Jupiter due to its very short predicted orbital period (3.9 days) and moderately hot equilibrium temperature (1114 K) (EXOFOP, 2023). As there was no statistical analysis done for false positive validation, future work can be done to prove the transit we are observing is in fact an exoplanet. As stated in Section 4.1, we have inconclusive results as to whether or not this signal was caused by a NEB, which may be causing a false positive to occur. Further observations and analyses can be done to rule out these concerns and prove the existence of TOI-3873.01. Other methods such as radial velocity measurements, spectroscopy, etc, can be then used to find out more about its true properties, atmosphere, and its habitability potential.

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