Ground-based light curve follow-up validation observations of TESS object of interest TOI 3945.01

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Abstract
The goal of this observational study is to perform follow-up investigations on a potential exoplanet discovered by the Transiting Exoplanet Survey Satellite (TESS), and validate if the findings by TESS are accurate. Potential exoplanet TOI-3945.01 was discovered in 2021, and our observational study aims to confirm the existence of this exoplanet. This study was done through George Mason University's 0.8m telescope, ansvr, AstroImageJ, and NASA's Exoplanet Archives to create a seeing profile, light curve, dmag vs RMS, and other results to determine if an exoplanet transit has occurred. The results of our observation show that although a transit was observed, it was not within the expected ingress and egress times, and more further investigations will need to be performed to verify this transit.

Introduction
Exoplanet transits are an important method in the search for and study of exoplanets, which allows astronomers to detect planets outside our solar system. When a planet passes in front of its host star, it causes a temporary dimming of the star's light, which can be detected and analyzed to determine the planet's size, orbit, and other characteristics. The Transiting Exoplanet Survey Satellite (TESS) is a space telescope launched by NASA in 2018, with the mission of detecting exoplanets using the transit method (Adkins, 2023). TESS has identified thousands of potential exoplanet candidates, each requiring further validation to confirm their existence and characteristics.

TESS has identified thousands of potential candidates, and that brings a need for them to be validated. It needs to be confirmed that the observed transits are actually caused by exoplanets, and not by some other phenomena such as binary stars or stellar variability.

Even though there's been progress with validation TESS Objects of Interest, many of them remain unvalidated. Our goals in this investigation are to verify the existence of TOI 3945.01, building on the foundation laid by earlier studies, aiming to fill the gap in the validation of TOI 3945.01.

In this paper, we present follow-up observations of TOI 3945.01 TOI 3945.01 has a radius of about 9.6 Earth radii, and has an orbital period of around 4.46 days. 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 and George Mason University's 0.8m telescope. Following this, Section 3 will delve into an analysis of the TESS light curve for TOI-3945.01 and our ground-based light curve analysis. In Section 4, we will present our light curve

results. Finally, Section 5 will discuss our findings, and Section 6 will present our conclusions and future work.

Observations

In Section 2.1, we present the TESS Object of Interest 3945.01 and its candidate properties, and information regarding its hoststar's properties. In Section 2.2, we present the light curves gathered by the TESS sector. Finally, Section 2.3 presents the observational data collected by George Mason University's 0.8m telescope.

Section 2.1

In 2021, the TESS system identified a potential planet while observing the star of TOI 3945, a star with an RA of 22:19:57 and a DEC of 62:39:24. Additionally, it has a stellar effective temperature of ~5472, a stellar luminosity of ~0.21345, a stellar density of ~0.47008, a stellar mass of ~0.96, a stellar radius of ~1.42262, and a stellar surface gravity of ~4.11416. The potential candidate planet, TOI-3945.01, has an equilibrium temperature of 830 K, an orbital period of ~4.46384, a planet radius (earth radius) of ~9.59744, a transit depth of ~0.3791, and a transit duration of 1.556 +- 0.323.

Section 2.2

Following the data collection of TOI-3945.01, TESS used this information to create light curves to analyze the potential exoplanet. Published to Exoplanet Follow-Up Observing Program (ExoFOP) on 2022-08-08, Figure 1, the TESS light curve, shows a potential transit between the predicted ingress 0.748 and predicted egress 0.810, which finalized TOI-3945.01 as a potential exoplanet (ExoFOP, n.d.).

Section 2.3

Following the potential discovery of TOI-3945.01, George Mason University used its 0.8m telescope with an R filter to perform follow-up observations of the exoplanet to truly confirm its existence. On 2024-06-25, the telescope began its observations at 21:50 and stopped at 04:33 (EST), had a predicted ingress at 0.628, and predicted egress at 0.690. Using TOI-3945.01's RA of 22:19:57.62, a DEC of 62:39:23.85, and an R filter, we captured around 180 90s exposures of the exoplanet.

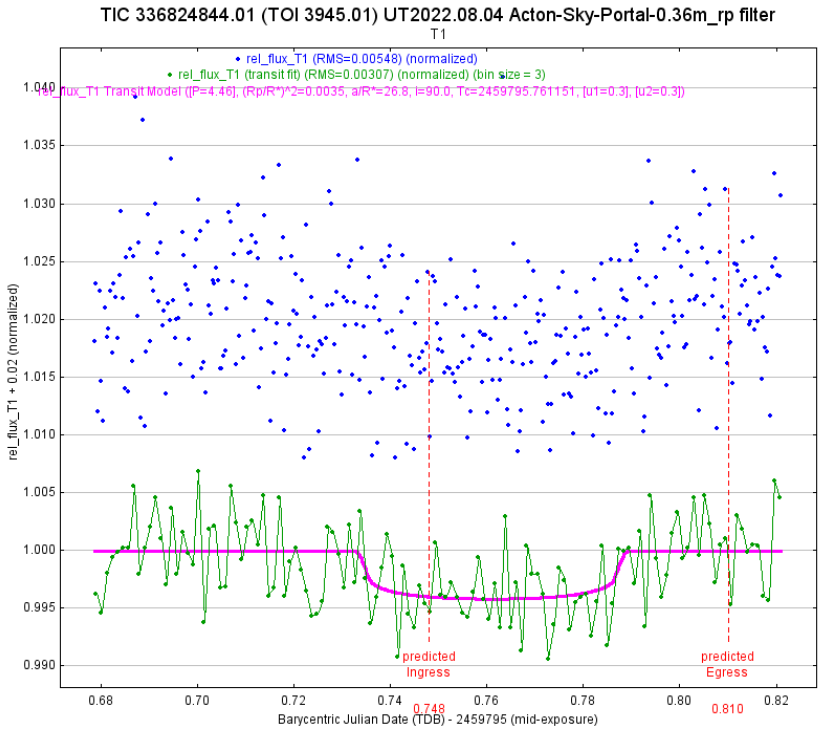

Figure 1

Analysis

In Section 3, we present our tools used to analyze the TESS sector light curve using AstroImageJ/ExoFASTv1/ExoFASTv2, and our analysis of the ground-based light curve using AstroImageJ.

Section 3.1

To begin with, we made sure that AstroImageJ was installed correctly and with all its dependencies. Then, we checked that ansvr was installed as well, with the correct indexes to allow for plate-solving later. In AstroImageJ, we first imported all of the sciences, and then did data reduction with the darks and flats. After the sciences were plate-solved using the master darks and flats, the images were aligned, and reference stars were selected. This created the seeing profile (Figure 2) of the data, as well as a dmagRMS-plot (Figure 3) to identify and remove any stars that may interfere with the data. Multi-aperture photometry was then done after stars were removed through the Aperture Photometry tool, creating a final light curve.

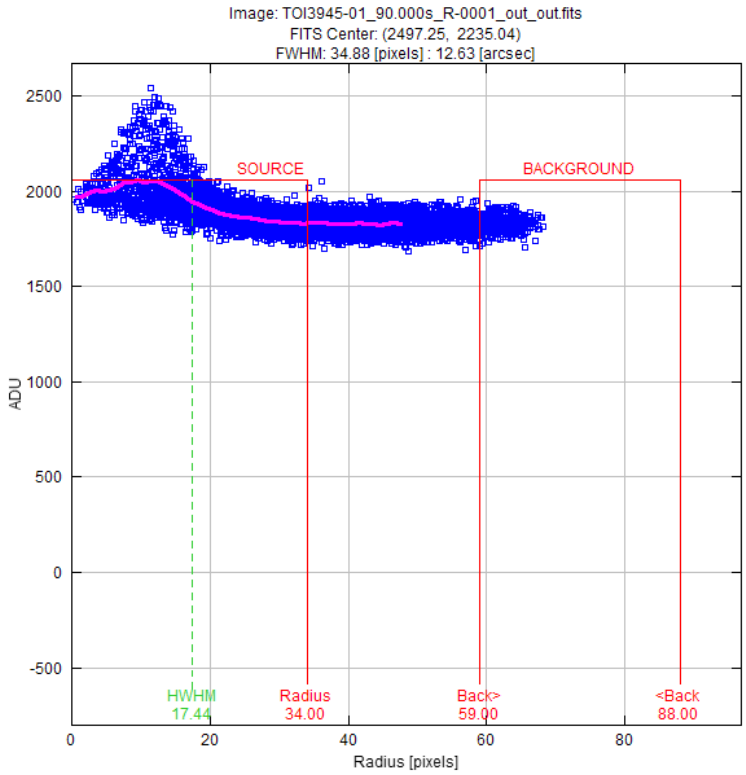

Figure 2

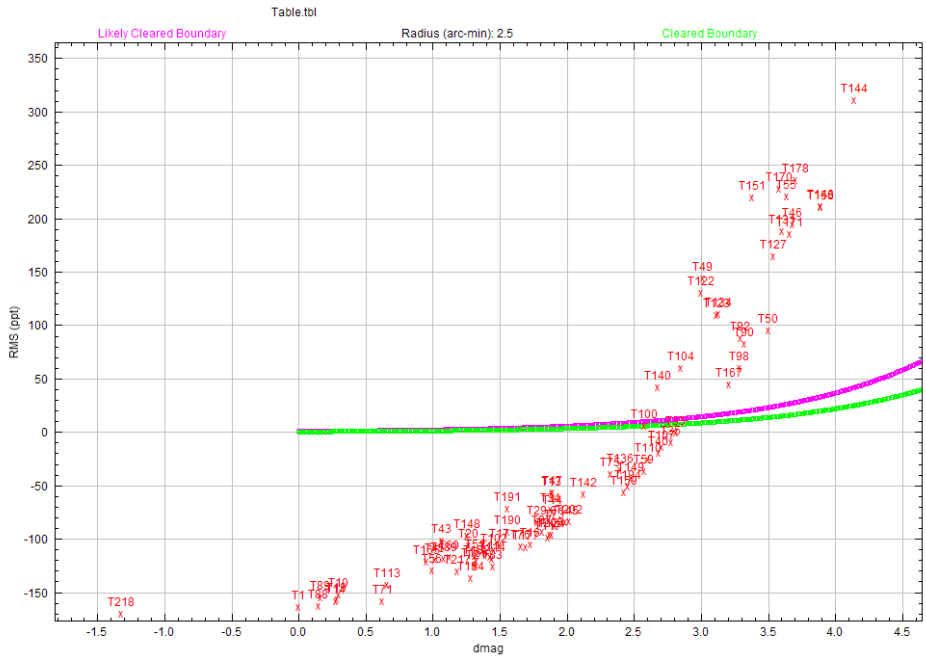

Figure 3

Results

In this section, we present the results that we obtained using the data collected and tools from AstroImageJ. Figure 4 is the final light curve that was generated using the Multi-Aperture

function in AstroImageJ. The red data points represent the normalized relative flux of the target, while the red line is the transit model of the target. The ground based light curve clearly shows a dip near, but not perfectly in, the ingress and egress lines. Similar to previous papers, the transit length was consistent and roughly the same, as well as the P value.

Figure 4

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

Using ground based photometry, we confirmed the planetary nature of candidate exoplanet TOI 3945.01. Although the fit/normalize region was unable to be moved correctly to perfectly fit the transit, the anticipated time, duration, and depth of the transit signal, as detected through our follow-up observations, reasonably corresponds with the predicted and measured values identified by TESS. This further reinforces the fact that there is a genuine transit signal, and that TOI 3945.01 is an actual exoplanet candidate.

Section 5.2

The light curve we generated matched the light curve that was generated two years ago (Figure 1). We also got the exact same P value (P = 4.46) as the other light curve from 2 years ago.

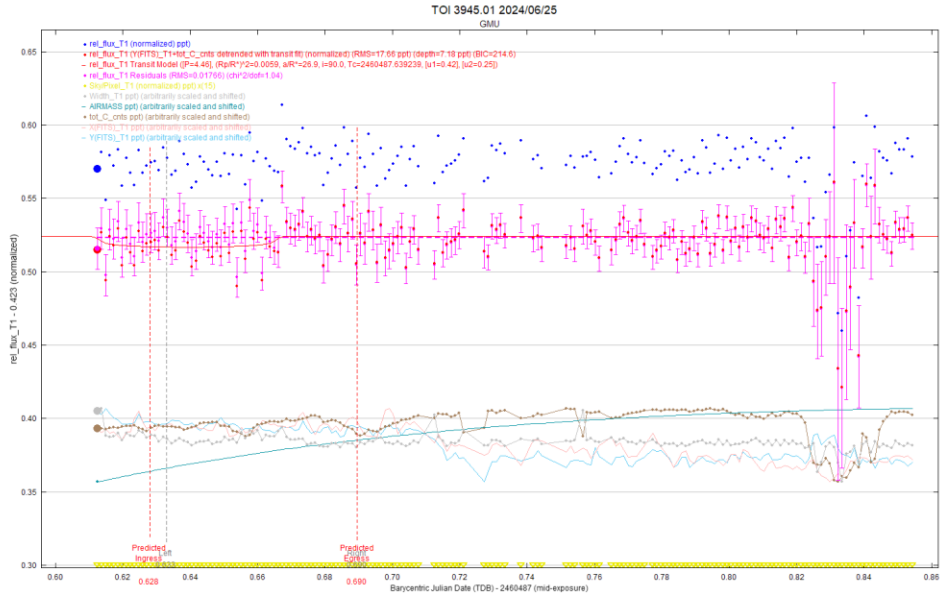

Figure 4.1 Adjusted fit/normalize region

Conclusions

From our results and observations, we concluded that TOI 3945.01 is likely an actual exoplanet candidate. We created a ground based light curve of the transit of TOI 3945.01, and the light curve clearly showed a transit.

Further analysis could be done on TOI 3945.01 in the future. Since the planetary nature of it is already confirmed, there could be further testing done in the future to confirm its characteristics. In addition, we were unable to perform false positive testing for TOI 3945.01, so that can be done in future research.

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