Draft version September 19, 2024
Typeset using LaTeX **twocolumn** style in AASTeX631

Ground-Based Follow-up Observations of TOI 3736 a

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ABSTRACT

Ground-based follow-up observations of exoplanet candidates observed by the TESS mission are crucial to ruling out false positives and confirming exoplanet properties. In this paper, we analyze and interpret observations made by the George Mason University Observatory 0.8 m telescope of TESS TOI 3736 a. An argument for the exoplanet status of TOI 3736 a is presented alongside several lines of evidence, including the observed transit depth, duration, and periodicity, which are consistent with the presence of a large, hot-jupiter-like planet in close orbit around its host star. In addition, we highlight differences and similarities between the target and similar exoplanets. To further verify the planetary status of TOI 3736 a, we outline potential future work, including high-resolution spectroscopy.

Keywords: Transit photometry, Exoplanet astronomy

1. INTRODUCTION

The exploration of space has always captivated humanity, with the discovery of exoplanets marking one of the most exciting frontiers in recent astronomical research. The Kepler Space Telescope pioneered the transit detection method, enabling the discovery of hundreds of exoplanets by monitoring the dimming of stars as planets passed in front of them (Basri et al. 2005). This technique set the stage for the launch of the Transiting Exoplanet Survey Satellite (TESS), which has expanded our understanding by identifying a wide variety of exoplanets (Ricker et al. 2014). TESS operates by scanning large swaths of the sky, focusing on nearby stars, and is predicted to find over 14,000 exoplanets (Barclay et al. 2018). The sheer volume of these candidates presents a significant challenge, as confirming whether each one is truly an exoplanet requires careful analysis. This is where ground-based follow-up observations become crucial, providing the necessary data to verify TESS's findings and enhance our understanding of these distant worlds. These observations help to confirm the existence of exoplanets by ruling out false positives caused by other astrophysical phenomena, such as binary star systems or stellar activity (Deeg & Alonso 2024). Additionally, ground-based telescopes can measure the masses and orbital parameters of these exoplanets, providing essential data to determine their compositions and potential habitability (Colón & Ford 2009). By combining space and ground-based observations, we can ensure the validity of new exoplanet discoveries.

This paper covers ground-based follow-up observations of TOI 3736 a, an exoplanet candidate that orbits a class F star. This paper aims to examine whether transit information of TOI 3736 a is consistent with expectations as measured by TESS.

In Section 2, we will describe our findings from TESS and the George Mason University 0.8m telescope for TOI 3637 a. Section 3 will delve into our analysis of the TESS light curve and the ground-based light curve for TOI 3637 a. We will then present the results from our light curve analysis in Section 4. Section 5 will be dedicated to discussing these results, and we'll conclude with our findings and outline the future research in Section 6.

2. OBSERVATIONS

In this section, we go over observations of that target. In Section 2.1, we will present TESS Object of Interest 3736.01 along with a summary of its properties from archival sources such as the TESS Input Catalog. In Section 2.2, we will present the TESS sector light curve. Then, in Section 2.2, we will summarize the observational data collected using the George Mason University 0.8m telescope.

2.1. *TOI 3736*

TOI-3736 a (Stassun et al. 2019) orbits a star with an effective temperature of $6876_{\pm 122.0}$ K, V magnitude of $13.811_{\pm 0.057}$ and log(g) of 4.103. TOI-3736 a has a radius of 1.663 R_j and a period of 2.209 days. It has an equilibrium temperature of 2086.959.

2.2. *TESS Light Curve*

The TESS mission observed TOI-3736 during Observation Sector 59 from November 26 through December 23, 2022 on orbits 135 and 136. The light curve files store information about flux a time interval of 2 minutes and 20 seconds. This data is obtained using Simple Aperture Photometry (SAP). The images were processed by the Science Processing Operations Center (SPOC) at NASA Ames Research Center, obtaining photometric and astrometric information for individual stars. It generates target light curve files containing photometric analysis and time series data (Jenkins et al. 2016).

2.3. *GMU Observational Data*

The ground-based follow up observations were conducted at the George Mason University Observatory on 2024-01-11 using the R filter on a 32" Ritchey-Chretien Telescope. The observation session started at 18:10 and concluded at 4:45, during which we collected a total of 145 exposures, each with an exposure time of 90 seconds.

3. ANALYSIS

In Section 3.1, we present analysis of TESS Sector Light Curve. In Section 3.2, we present our analysis of the ground-based light curve using AstroImageJ (AIJ).

3.1. *Analysis of TESS Light Curve*

The TESS sector light curves were retrieved from the Mikulski Archive for Space Telescopes on August 2nd, 2024 in the form of a lc.fits file.

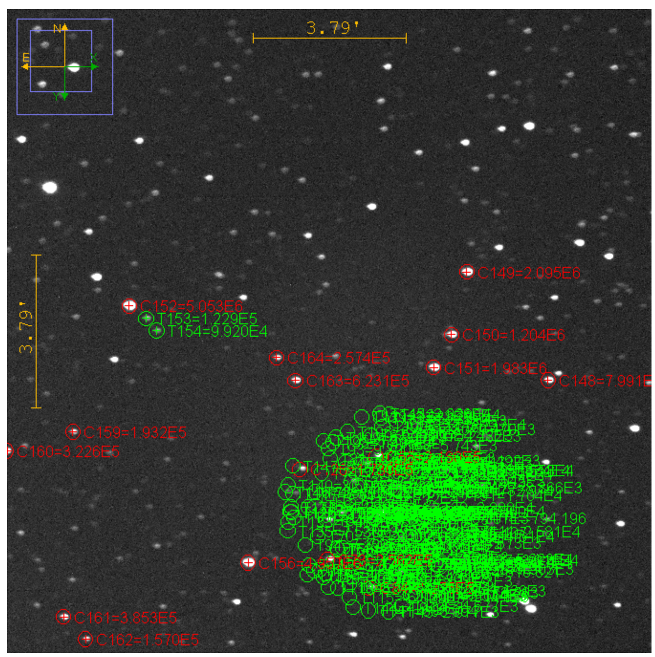
3.2. *Ground-Based Light Curve*

Extraction of a light curve from ground-based observations was conducted with the use of AIJ. Dark subtraction was carried out to reduce noise consistently produced by the sensor, followed by flat division to further decrease noise. This reduction process was carried out in AIJ before plate-solving the sciences. The darks were taken with the same exposure time as the science images. Plate-solving was done with the astrometry.net API through Alnitak (oalfaro2 2021). We conducted a comprehensive analysis to generate a light curve from plate-solved, data-reduced astronomical images. The procedure commenced with the importation of a virtual stack of aligned science images, following a careful review of the TFOP SG1 guidelines to ensure adherence to the prescribed file naming conventions. To perform aperture photometry, we first determined the appropriate aperture size by utilizing the "Aperture Photometry Tool" within AIJ. The target star was identified on an initial image, and its corresponding aperture and annuli radius values were derived using the "Seeing Profile" tool. To perform multi-aperture phomotetry, A 2.5" circular region was temporarily placed around the target star and the corresponding Gaia star .radec file was overlaid onto the image. This facilitated the selection of suitable reference stars, which were chosen based on their similarity in size and brightness to the target star. The differential flux of the target star was calculated by AIJ through equation 1, where $Flux_d$ represents differential flux, F_t is the integrated count of the target star aperture, and F_{ci} is the integrated count from the i-th comparison star aperture.

$$Flux_d = \frac{F_t}{\sum_{i=1}^{n} F_{ri}} \tag{1}$$

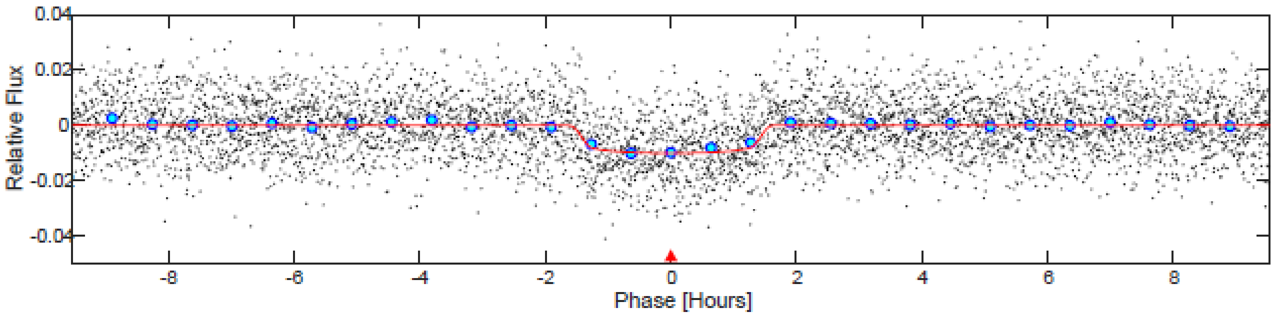
To mitigate potential inaccuracies, reference stars located near the image edges were excluded to avoid the effects of drift in later images. The final selection is shown in figure 1. The multi-aperture photometry

Figure 1. Aperture selections for multi-aperture photometry in AIJ



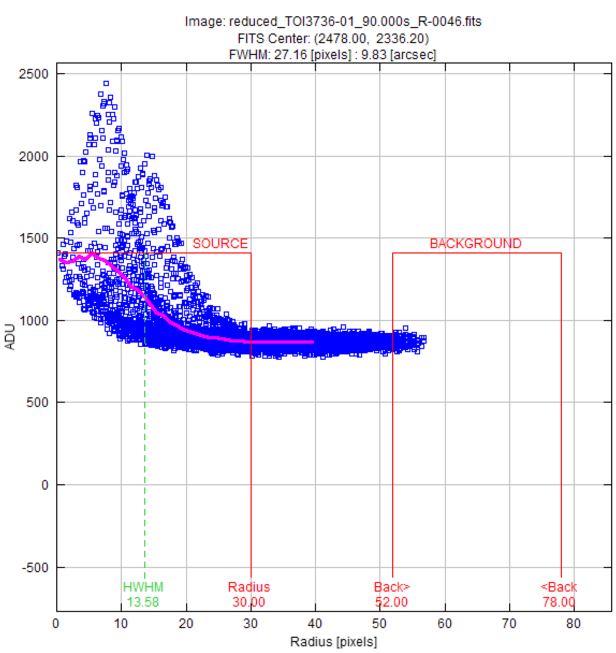
process was then executed, generating a measurement table for further analysis. With the measurement table we initiated the light curve analysis. The table was loaded into AIJ, and a default plotting template was applied to ensure compliance with TESS/K2 reporting guidelines. In the "Multi-plot Main" window, the predicted ingress and egress times were set, alongside de-

Figure 2. TESS Sector Light Curve of TOI 3736 a



tails of the observational setup. The target's orbital and stellar parameters were entered into the "Data Set 2 Fit Settings" window, including the relevant limb-darkening coefficients (Eastman et al. 2013). The analysis continued with a systematic review of the flux measurements for each reference star, identifying and excluding any stars that exhibited significant variation or scattering. The aperture and measurement table files were updated to reflect these adjustments. We conducted a neighbor star examination to verify the clearance of surrounding stars. Detrending was applied using airmass, Width_T1, and Sky/Pixel_T1, and the final results were used to generate the light curve. To check the statistical significance of the measured transit and to further rule out the possibility of a false positive, bayesian statistical analysis was performed using a Markov Chain Monte Carlo (MCMC) analysis with EXOFAST. By providing the appropriate priors and the relative flux over time, we were able to generate a probabilistic distribution of the radius of TOI 3736 a, along with similar distributions for other characteristic features.

Figure 3. Seeing profile of one reduced image



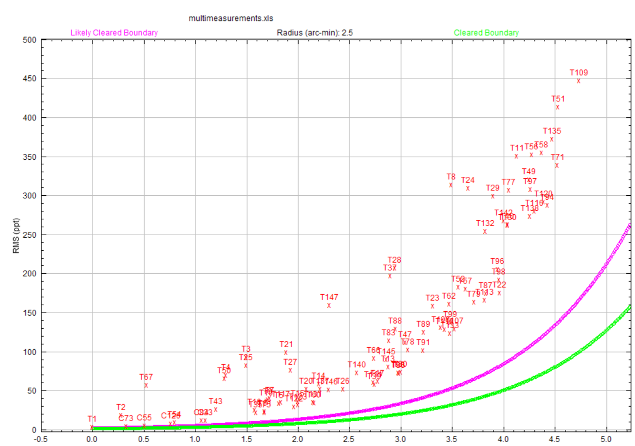
4. RESULTS

In this section, we reveal the results of our analysis. Section 4.1 will contain the light curve generated by TESS. Section 4.2 will present the results of the ground-based follow up observations.

4.1. *TESS Light Curve*

The relative flux light curve generated by TESS on the nights it observed the target is presented in figure 2.

Figure 4. NEB check plot of nearby stars



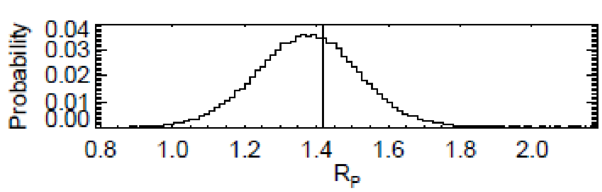
4.2. *Ground-Based Follow-Up Observations*

The results of the ground-based follow-up observations are presented in this section. Figure 5 shows the light curve created using AIJ. The relative flux of the target star is plotted over time, as well as the transit model and residuals. Multiple reference stars are also graphed

Figure 5. Ground-Based Light Curve of TOI 3736 a

to provide context for the target star. The seeing profile for one for the reduced images is shown in figure 3. The results of the NEB check are in figure 4, with a line indicating the likely-cleared boundary and the cleared boundary. The resulting distribution from the MCMC analysis of the transit is shown in figure 6. The distribution shows the expected potential radii of TOI3736 a and the probability of the target being that radius.

Figure 6. EXOFAST MCMC distribution for planet radius



5. DISCUSSION

In Section 5.1, we will discuss an interpretation of our findings. In Section 5.2, we will contextualize our results within the broader field of follow-up studies on candidate exoplanets from the NASA TESS mission.

5.1. *Interpretation*

As seen in figure 5, there is a clear detection of a transit consistent with the predicted measures of time, length, and depth. The observed transit from the ground-based telescope happened during the predicted ingress and egress times from 0.523 to 0.660 BJD. The relative flux of the reference stars remained constant through this timeframe, whereas the target star observed a decrease in relative flux of 7.13 ppt. This indicates that TOI 3736 a experienced a transit time consistent with past predictions. Furthermore, this transit depth is very similar to the TESS light curve shown in figure 2, which had a decrease in relative flux of around 10 ppt. Figure 3 shows that that the flux from stars was relatively spread out, with a HWHM of 13.54 pixels. Figure 4 shows the RMS of the neighboring stars to check for a potential nearby eclipsing binary (NEB). Very few of the stars are below the cleared boundary or the likely cleared boundary, suggesting the potential existence of a NEB. However, the individual light curves for the stars do not reveal a transit-like signal at transit time of TOI3736 a, ultimately resulting in inconclusive evidence on whether a nearby eclipsing binary could exist. Figure 6 shows the expected radii of TOI

3736 a following a MCMC algorithm. The Chi^2/dof of the analysis was 0.99485440, suggesting a very accurate fit. The figure shows that there is 0 probability of the target exoplanet having a radius of 0, strongly suggesting the existence of an exoplanet with some nonzero radius. The presented results encourage the conclusion that TOI 3736 a is indeed an exoplanet.

5.2. *Context*

TOI 3736 a can be considered a hot Jupiter based on its equilibrium temperature, planetary radius, and orbital period. One of the most well-studied hot Jupiters, WASP-12b, orbits its star in just over a day and has a temperature exceeding 2500 K (Hebb et al. 2009). Our studied exoplanet shares similar orbital characteristics but exhibits a slightly lower temperature. Hot Jupiters exhibit a wide range of characteristics, as shown by the exoplanet Kepler-7b. Known for its low density and large size, Kepler-7b provides a contrast to our planet, which has a higher density and smaller radius (Latham et al. 2010). However, both planets share the characteristic of close orbital proximity to their stars.

6. CONCLUSIONS AND FUTURE WORK

This paper presented and examined ground-based follow-up observations on TOI 3736 a. followed by statistical and numerical analysis of both the TESS light curve and the information presented in observations from the GMU observatory. The obervations from the ground revealed a transit depth of 7 ppt during the expected transit timeframe, similar to the 10 ppt transit depth observed by TESS. To support the conclusion that TOI 3736 a is indeed an exoplanet, several checks were done, including checks for NEBs and a MCMC analysis of the transit.

Future work is necessary to confirm the status of TOI 3736 a as an exoplanet. THE NEB check proved inconclusive, so a reexamination in the future may be necessary. More detailed statistical false-positive validation analysis should be carried out to reduce the likelihood of a false positive. High contrast imaging should be used to inspect nearby faint stars. We encourage spectroscopy to be performed on the target to see if there are any binaries present in the spectra and rule out large radial velocity changes.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

Some/all of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts.

This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

Facilities: Exoplanet Archive, MAST, Gaia

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