Ground-Based Light Curve Follow-Up Validation Observations of TESS Object of Interest (TOI) 5886.01

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Abstract

NASA's Transiting Exoplanet Survey Satellite (TESS) is using a transit photometry method to look for dips in the brightness of the nearest 200,000 stars to scan for possible exoplanets. This paper presents the results of follow-up ground-based observations of TESS Object of Interest (TOI) 5886.01, also identified as TIC (TESS Input Catalog) 15682927, and aims to determine if the transit detected on TOI 5886.01 represents a potential exoplanet. Utilizing Python and Jupyter Notebook, data from TESS, and analyze our own data from GMU Observatory (collected on 06/18/2024) with AstroImageJ, our evaluation suggests that TOI 5886.01 is likely a hot Jupiter.

Introduction

The study of exoplanets is very important in astronomy. Scientists have been finding ways to accurately detect and observe them. The first discovery of two exoplanets was in 1922 by Poltergeist and Phobetor, orbiting a pulsar called PSR B1257+12 (*The history of exoplanets*, n.d.). Since then, many technological advancements and methods have been developed, with the most common being the transit photometry method. When an object orbiting a host star passes in front of it, the star's light dims slightly as observed from Earth, creating a "dip," and the light levels measure drops. By monitoring the light curve of a star through periodic observations, scientists analyze the shapes and fluctuations of the curve to determine if there is an exoplanet passing in front of the host star. This effect in brightness measurement may also reveal certain characteristics of stars and potentially the exoplanets that scientists are observing. For example, the brightness of the star can help astronomers determine its distance, whether it's within the "habitable zone," and its size and mass. The size and distance of the exoplanet from its star can be interpreted from the depth of the dips, and if observed over the right duration, features such as orbital period, eccentricity, and the possibility of additional planets within the star system (SMD Content Editors, 2024-a). All of these aspects can help astronomers theorize whether the exoplanet has the potential to sustain life and is worth further research.

Currently, more than 7,000 TESS object candidates are awaiting confirmation. Each candidate's name starts with TOI (TESS Object of Interest) followed by a series of numbers based on the order they were found. Confirmed exoplanets' names may be changed or remain the same, as seen with the confirmed exoplanet AU Mic b. Numerous published papers have recorded ground-based observations of these candidates, with around 500 candidates confirmed

(NASA, 2019). However, many more objects remain unanalyzed, and many existing findings are inconclusive.

In this paper, we take the opportunity to perform a ground-based observation and analyze one of the unconfirmed candidates, TOI-5886.01. Its host star is 1.92±0.08 times the radius of our sun with an effective temperature of 7542±254.4 Kelvin, more than 800 pc away from Earth (*NASA Exoplanet Archive*, 2019). This study is aiming to address the gaps and contribute new insights to the field. The goal of these observations is to determine whether the transit of the object on our candidate host star, TOI-5886.01, occurred at the expected time, observed duration, and depth, along with any evidence that shows whether the object is potentially a transiting exoplanet or a false positive.

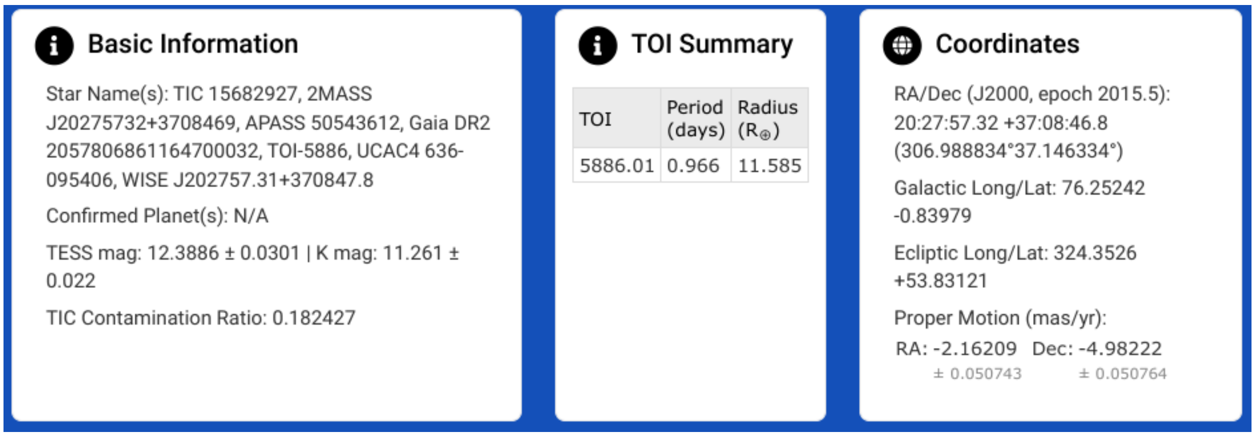
This paper is divided into several sections: **Method Section 1.1** presents the data retrieved from the TESS database, containing certain known characteristics of the object and its host star TOI-5886.01, which are key components for our analysis. **Method Section 1.2** details our own data collected through observation at George Mason University Observatory with an 0.8m telescope. **Method Section 2.1** explains how we analyzed our raw data into light curves and images, and **Section 2.2** describes how we retrieved TESS data. In **Results Sections 3.1** and **3.2**, we present all result images from our ground-based light curve analysis and the light curves obtained from TESS for TOI-5886.01. In the **Discussion** section, we compare our findings with TESS data and interpret possible results. Finally, we outline our conclusions and future work that we believe needs to be done.

Methods

1.1 - TESS Data

The data we retrieved from ExoFop for TOI-5886.01 was created on November 8th, 2022 and was last modified on March 7th, 2024.

Figure 1
Certain characteristics of TOI-5886.01 and object obtained from ExoFop



1.2 - GMU Telescope Observation

In this study, we performed our own ground-based observation and collected raw data of TOI-58860.1 using George Mason University Observatory, located in Fairfax, Virginia, -77:18:19.24 longitude, +38:49:41.5 latitude, and an altitude of 148.72.

Figure 2
Image of the moon for telescope trial run taken at GMU Observatory

The telescope is 0.8m, with 12.98 visual magnitude, and R filter. We observed a total of 223 Science images, 10 Flat and Dark images, each with 85s exposure time, starting from 21:50 UTC to 4:30 UTC on Tuesday, June 18th, 2024. The time of ingress of TOI-5886.01 during our time of observation is 0:32, and egress of 1:46.

2.1 - Analysis with AstroImageJ

In this study, we used AstroImageJ to create light curves for our target candidate, TOI-5886.01 from the raw data of our ground-based observation at GMU Observatory.

First, we downloaded all 243 captured and processed images from the GMU telescope. We separated them into science, flat, and dark images. We reduced the science images by removing any poor-quality images, such as those with streaking, targets out of focus, or blurriness. Next, we performed data reductions with the flat and dark images. Flat and dark images are taken to ensure that science images (images that will be analyzed) are as accurate and clear as possible by reducing noise and blocking light that could interfere with the final data.

Second, we centered each reduced science image to their corresponding RA and DEC coordinates, which are 20:27:57.32 +37:08:46.8. Centering them helps generate more accurate light curves that show the transit of TOI-5886.01. This process is known as plate solving.

Third, we performed multi-aperture photometry to generate a measurement table for TOI-5886.01, which was later used to produce the final light curve for our analysis (see **Results Figure 6**). The purpose of this process is to measure the brightness of our target star while accounting for the effects of surrounding objects and background noise. The measurement table shows the flux changes of our target star, Gaia stars, and reference stars that have similar brightness (see **Results Figures 3** and **4**).

To produce light curves for TOI-5886.01, we input data collected from TESS, such as the object's orbital period, host star radius, temperature, etc. Then, given our ingress and egress, we converted it to BJD (Barycentric Julian Date), a standard time unit used in astronomy. To ensure accurate light curves, we eliminated reference stars and other sources that caused significant variation in our plot. We performed the NEB check to identify potential eclipse binary star systems that might be mistaken for exoplanets, which could lead to false positives. We checked this using dmagRMS to assess consistency and identify any outliers in the plot. Fortunately, TOI-5886.01 is not an outlier (see **Results Figure 5**).

2.2 - Analysis with TESS Data

We used the NASA Exoplanet Archive (NASA, 2019) and ExoFop (Caltech, n.d.-b) to retrieve measurements of TOI-5886.01 provided by TESS. We utilized Python with Jupyter Notebook to convert TESS .fits data into flux plot light curves for a closer analysis of the transit dips. These measurements helped us produce our own light curves and analysis, as they contain essential characteristics of our host star and target object, which are crucial for evaluating TOI-5886.01. We also retrieved light curves obtained by TESS to compare with our own (see **Results**).

Results

3.1 - Ground-based Light Curves

Figure 3

AstroImageJ Seeing Profile of TOI-5886.01. Photometry aperture radius, inner annulus radius, and outer annulus radius is 36, 63, and 94 pixels.

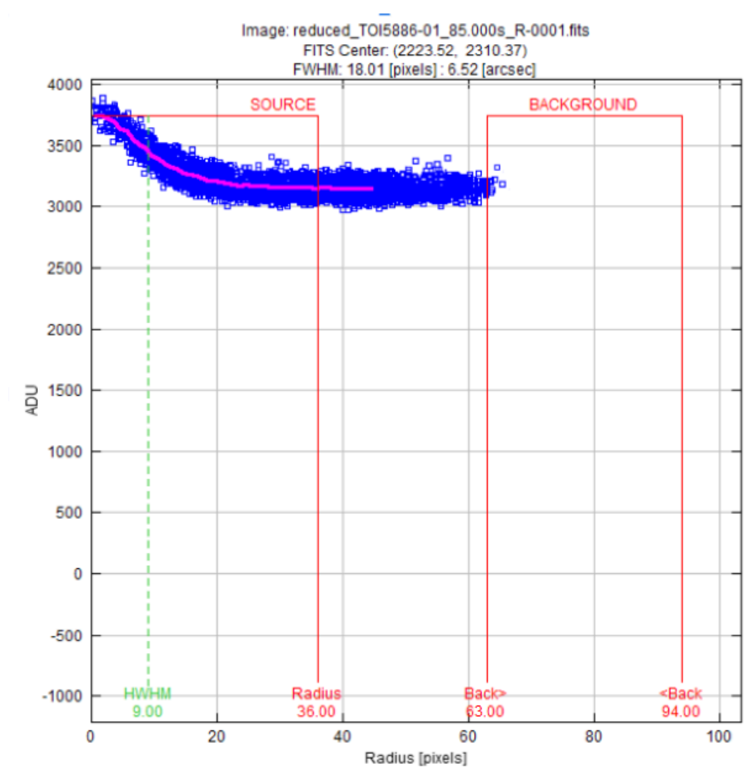


Figure 4

AstroImageJ aperture of TOI-5886.01, Gaia, and all reference stars

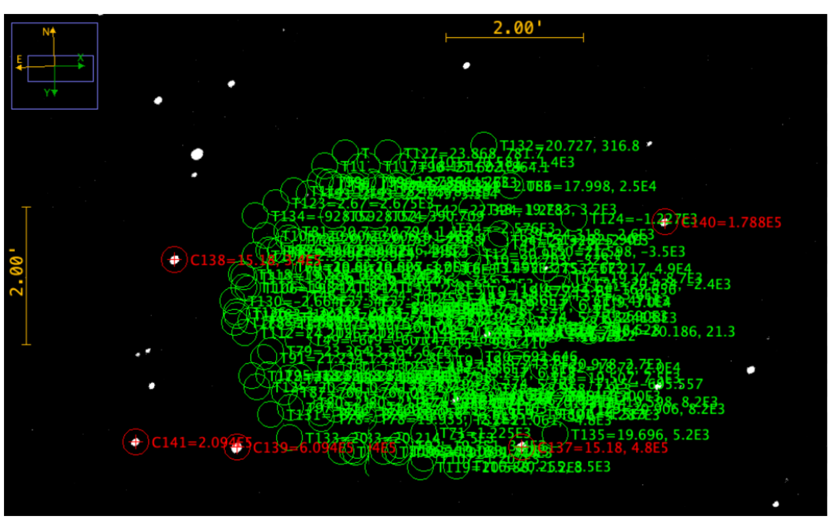


Figure 5

NEB Check - dmagRMS plot of TOI-5886.01 (T1) and other stars

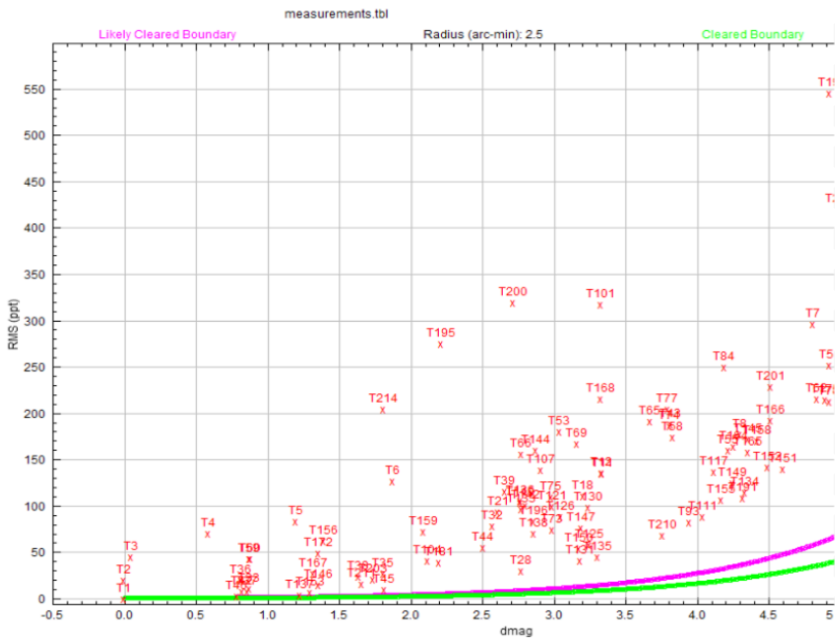
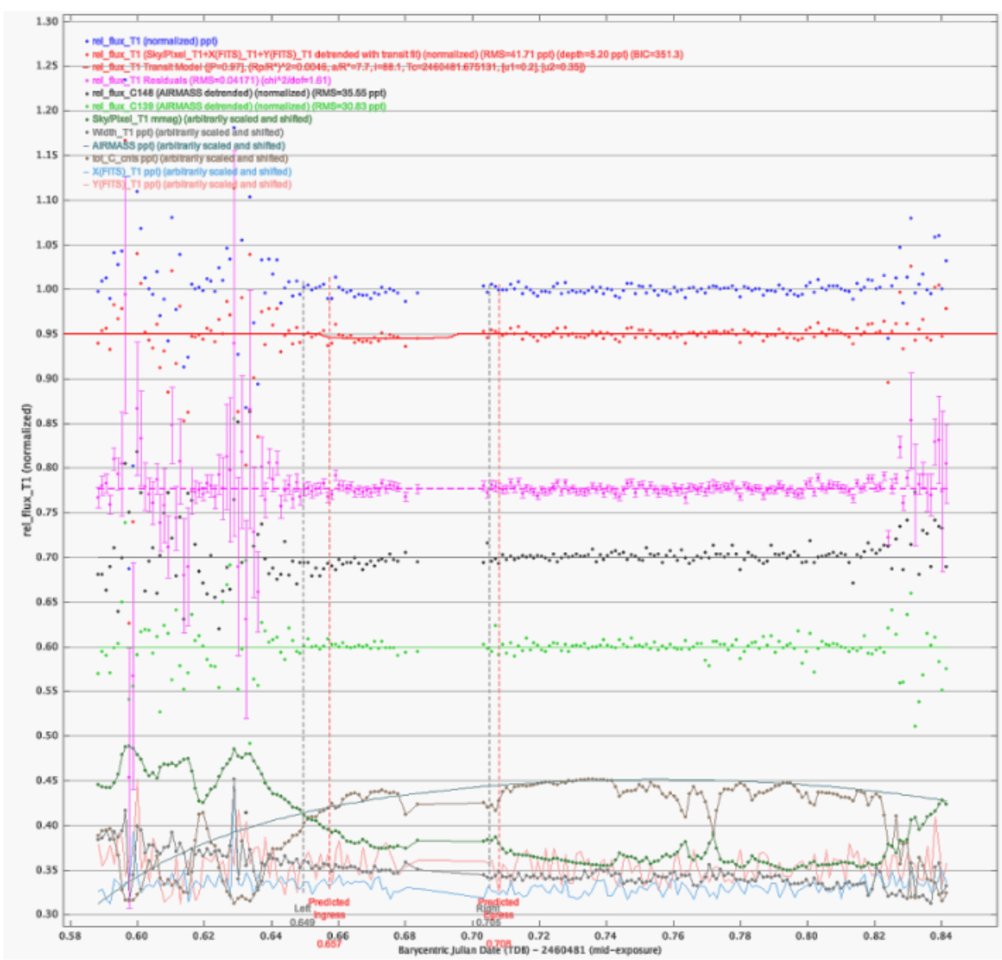


Figure 6

AstroImageJ final light curve of TOI-5886.01. Transit occur around 0.657 to 0.708 BJD



3.2 - TESS Light Curves

Figure 7
TESS dmagRMS plot of TOI-5886.01 (T1) other stars

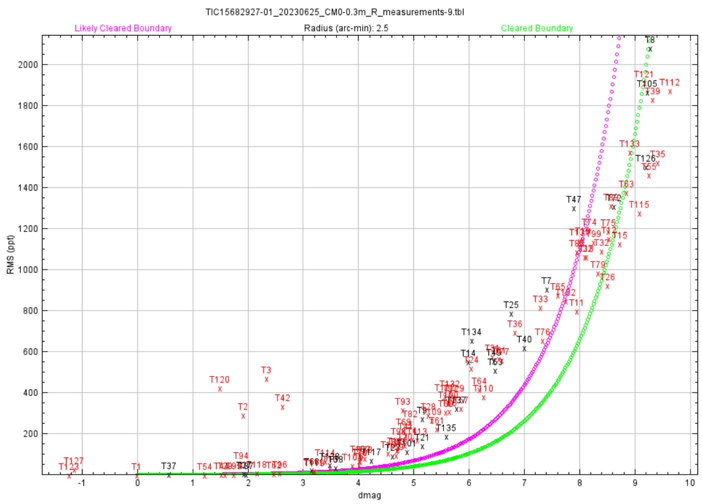


Figure 8
TESS aperture of TOI-5886.01, and Gaia, and all reference stars

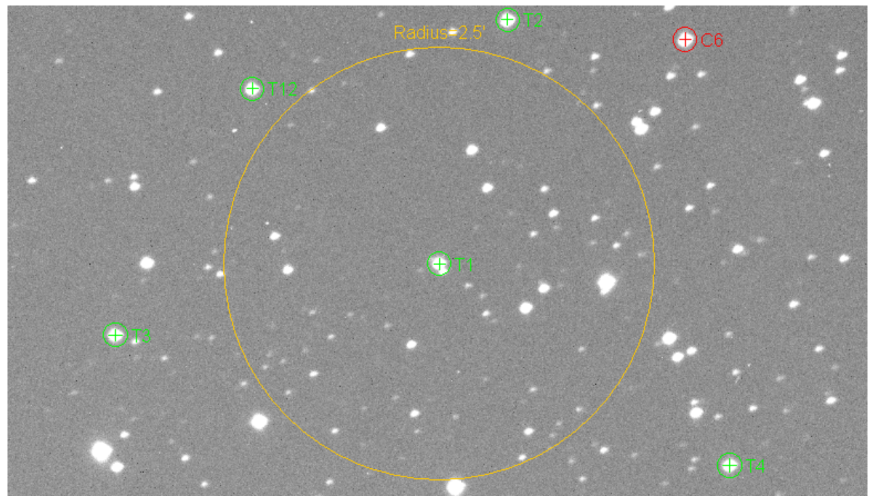


Figure 9
SAI-2.5m speckle sensitivity curve that see if there are any faint nearby stars that could contaminate the Tess beam and indicate a nearby eclipsing binary

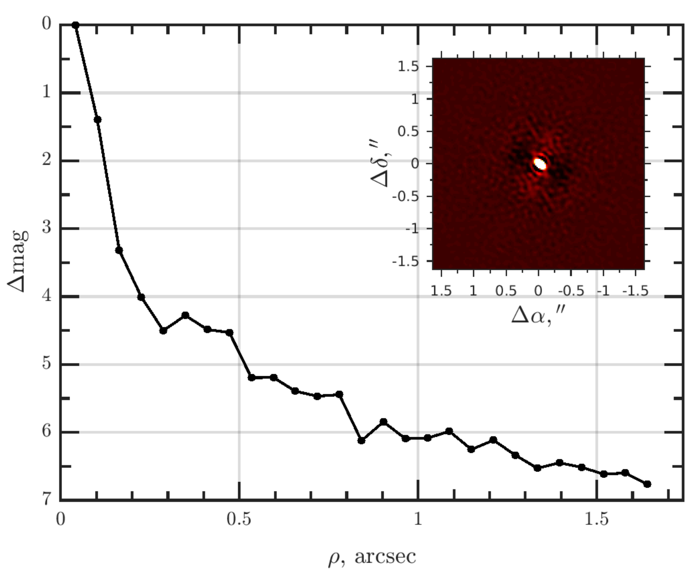


Figure 10
TESS plot light curve processed through Jupyter Notebook

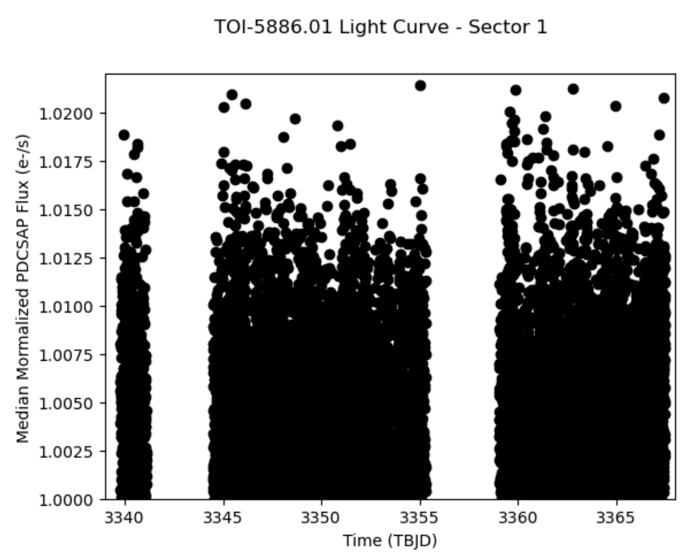


Figure 11

TESS light curve of TOI-5886.01

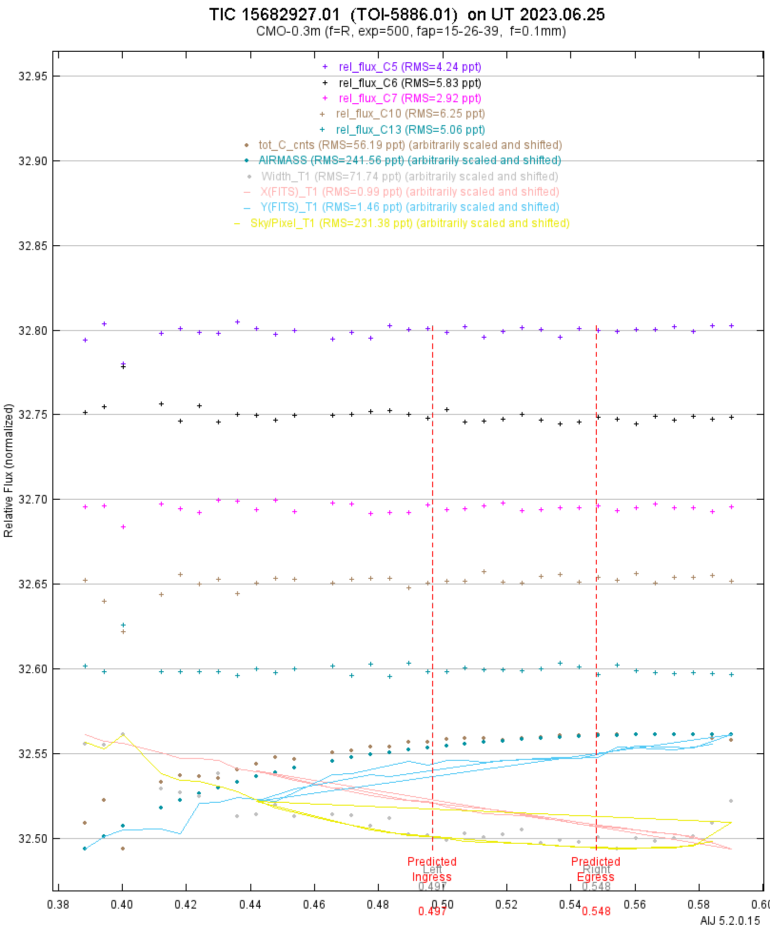
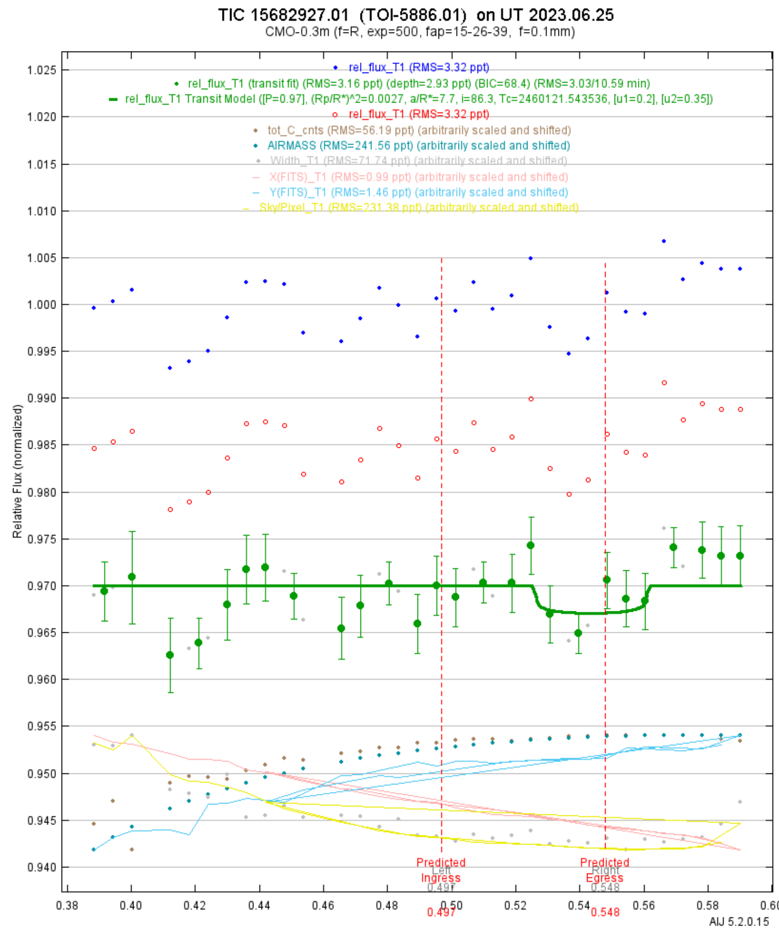


Figure 12

TESS light curve of TOI-5886.01



Discussion

Overall, our ground-based observations and TESS data strongly suggest that the transit of TOI-5886.01 could be an exoplanet, probably a hot Jupiter—a type of exoplanet that orbits very close to its host star. The predicted ingress and egress of the transit were between 0.657 and 0.708 BJD (red dotted lines). However, the actual transit occurred between 0.649 and 0.705 BJD (grey dotted lines), slightly earlier and longer than predicted (see **Figure 6**). This discrepancy could be due to differences in observation times and durations. Other potential explanations include a slightly elliptical orbit or a non-spherical shape, suggesting the object could be an asteroid. Both scenarios might slightly alter the timing of the transit. Atmospheric effects, such as turbulence, clouds, and changes in air density, could also distort the observed transit times, which may explain the irregular fluctuations (shown in pink) at the beginning of our final light curve (see **Figure 6**).

Despite these variations, our light curve indicates a transit with a depth of 5.20 ppt. This depth is deeper yet consistent with the predicted depth of 3.414575 ± 0.325762 mmag (NASA, 2019) or approximately 3.709 ppt (*Converting PPM to magnitudes - Kepler data*, 2021) and the TESS light curve of 2.93 ppt (see **Figures 11** and **12**). Orbital eccentricity, as previously mentioned, could account for the variations in light received and blocked. A deeper transit depth might also suggest that the exoplanet is larger than predicted by TESS and is very close to its host star, TOI-5886.01, thereby blocking more light. These conditions are consistent with the characteristics of a hot Jupiter if the object is confirmed as an exoplanet, given its radius of 11.5845 ± 0.754258 times that of Earth, an orbital period of less than 1 day, and a temperature of 2186 Kelvin (*NASA Exoplanet Archive*, 2019).

The chi-squared test evaluates how well our transit model aligns with the data by comparing the squared differences between actual and expected data to the expected data. A chi-squared statistic closer to 1 indicates better alignment between the model and the data. Our reduced chi-squared statistic is 1.61, suggesting that our model and data align reasonably well, though some improvements are possible. Our RMS came out to be 41.71, a little over the standard value of 40. This indicates a high level of variability or noise in the data, meaning our detection is less accurate. Large fluctuations before the transit ingress likely contribute to this statistic. These variations could be attributed to atmospheric conditions such as humidity, clouds, high air density, and air pollution. Additionally, some data were lost during reductions, creating variation and gaps in our light curve.

Figure 10 shows that the brightness dips are similar in duration and depth, indicating a stable transit of the targeted object around its host star. This stability rules out the likelihood of the object being an asteroid, as asteroids have irregular shapes leading to uneven dips and varying gravitational forces. The dips are too deep to be caused by small space objects like asteroids and match the characteristics of a hot Jupiter, with the dips covering the measured light completely. Eclipsing binary stars, a potential false positive in our study, typically produce less consistent light curves due to brightness shifts as two stars orbit each other. Additionally, **Figure 9** SAI-2.5m speckle sensitivity curve doesn't seem to show a possibility of another star in the system. However, we could not entirely rule out the possibility of an eclipsing binary system in our NEB check. Almost every stars failed to pass the cleared boundary (in green) or the nearly cleared boundary (in magenta), and neither most stars in the NEB check produced by TESS (see **Figure 7**), rendering our NEB check inconclusive and leaving the possibility that the transit of TOI-5886.01 could be a false positive.

Conclusion & Future Work

Current evidence strongly suggests that the transit detected for TOI-5886.01 could be an exoplanet, possibly a hot Jupiter, due to its characteristics and interactions with its host star, TOI-5886.01. Data retrieved from the NASA Exoplanet Archive and processed using Python through Jupyter Notebook support the existence of this candidate. However, the NEB check from AstroImageJ using our own data observed through GMU Observatory indicates a failure to rule out the potential of a false positive. Therefore, additional research and data collection are necessary to confirm the status of TOI-5886.01 due to the limitations of this study.

Specific areas for improvement include conducting more frequent and repeated observations. Our study involved only a one-time observation of TOI-5886.01 with a duration of 6 hours and 40 minutes. Data reductions accounted for poor-images, environmental factors such as air pollution, humidity, and clouds, which might have affected the capture of the peak transit. Noise reductions through detrending or smoothing the light curve can help highlight potential transits more clearly. Conducting spectroscopy to analyze mass, density, and other properties is also recommended. Additionally, applying other scientific methods such as Radial Velocity and Gravitational Microlensing (SMD Content Editors, 2024-b) for comparison and detection of eclipsing binary stars or other star systems can help confirm or rule out false positives. These methods could be useful in examining the habitability and potential for life on this exoplanet. A deeper study on determining the status of TOI-5886.01 may provide valuable insights into planetary evolution, technological advancements, and contribute to the search for extraterrestrial life and habitability beyond Earth.

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