# Ground Based Light Curve Follow-Up Validation Observations of TOI-5868.01


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## Abstract

The Transiting Exoplanet Survey Satellite, or TESS, serves to search for and gather data about possible exoplanets using transit photometry. Candidate exoplanets identified as TESS Objects of Interests (TOIs) then go through follow-up ground based observations. This paper presents the follow-up research to confirm the existence of candidate exoplanet TOI-5868.01. To determine this, we conducted multi-aperture photometry using AstroImageJ and produced a light curve. Based on the light curve analysis, it is likely that TOI-5868.01 is an exoplanet and is a Hot Jupiter.


## Introduction

The question of whether there are worlds beyond our own has fueled the innate curiosity of humankind for years. That question has been answered by the discovery of the first exoplanet in 1992, but it has sparked an interest in finding more. The search for exoplanets has since boomed as a field in astronomy, as it allows us to understand the inner workings of our universe. We learn of the diversity of the wide range of types of planets formed, from Neptunians to Hot Jupiters to Super-Earths; each new planet provides scientists a greater understanding of planetary formation.

As such, there are several ways to detect an exoplanet. One of these ways is the transiting method. As a planet passes in front of its host star, the flux of the star decreases as the planet is blocking the light. We can detect these dips in stars via the transit photometry method. If there is a detection of a decrease in light, which is a transit, this indicates the presence of an exoplanet. To hunt for exoplanets, NASA launched the Transiting Exoplanet Survey Satellite (TESS) mission to search for candidate exoplanets using transit photometry. Any target TESS has deemed a potential candidate is cataloged as a TESS Object of Interest, or TOI. It is our duty to verify the planetary nature of these TOIs using ground-based light curve follow-up observations. This can be achieved through multi-aperture photometry.

This step is absolutely necessary as there are over seven thousand potential exoplanets discovered by TESS, however only around five hundred have been confirmed after ground-based follow-up observations. Ground-based observations can also tell us the planet's properties. For instance, three transiting exoplanets have been found to be Jupiter-sized (Saeed et. al, 2022). Such observations can be achieved using AstroImageJ, a software that can plot and analyze light curves from telescope data (Davoudi et. al, 2020). However, there are still thousands of candidate exoplanets that have yet to be confirmed.

In this paper, we present follow-up observations of TOI-5868.01. Our goal is to determine if the transit predicted by TESS happens at the predicted time, with the predicted ingress and egress times (in BJD), with the predicted depth (in ppt). We will use the software AstroImageJ for our analyses. We will use ExoFOP and the NASA Exoplanet Archive databases to obtain the parameters predicted by TESS (see **Section 2.1**).

In **Section 2**, we present our observations from TESS and the George Mason University 0.8m telescope. In **Section 3**, we present our analysis of the TESS light curve for TOI 5868.01 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

In **Section 2.1**, we present exoplanet and host star properties of TOI-5868, and in **Section 2.2**, we present the observation process

## TESS Observational Data - 2.1

The TESS Input Catalog (TIC) ID for TOI-5868 is 236158940. The Right Ascension (RA) and Declination (Dec) coordinates for TOI-5868.01 are 20:53:40.689s and +34:21:05.93s, respectively.

According to ExoFOP, the stellar parameters for TOI-5868 as observed by TESS are as follows:

- Solar radii: 2.406
- log(g): 3.849
- Effective temperature: 6875.79 K
- Metallicity: 0.067

Additionally, here are the planetary parameters for TOI-5868.01 as observed by TESS:

- Period: 2.678 days

- Depth of transit: 3.301 ppt
- Duration of transit: 2.885 hours
- Transit midpoint: 2459817.28767 BJD
- Equilibrium temperature: 1817 K

### GMU Telescope Observation Process - 2.2

We observed the host star on Tuesday, July 2, 2024 at 10:40 PM at the George Mason University telescope in Virginia. The telescope uses a 0.8m lens.

We observed a total of 290 science images, each with an exposure time of 65 seconds, using the R filter on the telescope.

## Analysis

**Section 3.1** presents the tools used to analyze TOI-5868.01. **Section 3.2** presents the analysis process using AstroImageJ.

### Analysis Tools - 3.1

AstroImageJ is a software that enables a user to conduct multi-aperture photometry, generate a light curve, and interpret data after importing an image stack. These specific tools are utilized in this study.

Jupyter Notebook is a web application that allows users to create tables, graphs, and other such visualizations with the help of various libraries and tools. It is useful because it allows the user to interpret data by running one cell of code at a time. We used Jupyter Notebook to run a backup-light curve to confirm the planetary nature of TOI-5868.01.

### Analysis and Light Curve Generation Using AstroImageJ - 3.1

First, we performed data reduction of the sciences to eliminate any distortions in the science images collected. Using AstroImageJ's CCD Data Processor and the DP Converter windows, we were able to create a master flat image with an exposure time of 3 seconds. Additionally, we created two master dark images: one with exposure time of 3 seconds to match that of the master flat image, and one with exposure time of 65 seconds to match that of the science images. Then, we dark-subtracted and flat-divided our raw sciences, resulting in reduced science images.

After this, we inspected each individual science, and removed ones that were not deemed helpful for analysis from the image stack. Some reasons the unhelpful sciences were removed from the stack include being blurry, the telescope was adjusting, or a satellite passed near the target star. In the end, out of the 290 science images collected, 148 were deemed useful.

We then plate-solved and aligned the remaining 148 science images. This was achieved by centering each reduced science image on the RA and Dec coordinates for TOI-5868. Ultimately, this process allows us to clean the data, leaving it without any unnecessary information. This step also saves time and space for further observation.

Now, to conduct ground-based light curve analysis, we first measured the aperture and annulus radius of our target star by selecting it from the image stack. Then, we conducted aperture photometry, from which we obtained a photometry radius of 40 pixels, an inner annulus radius of 70 pixels, and an outer annulus radius of 104 pixels (**Figure 1**).

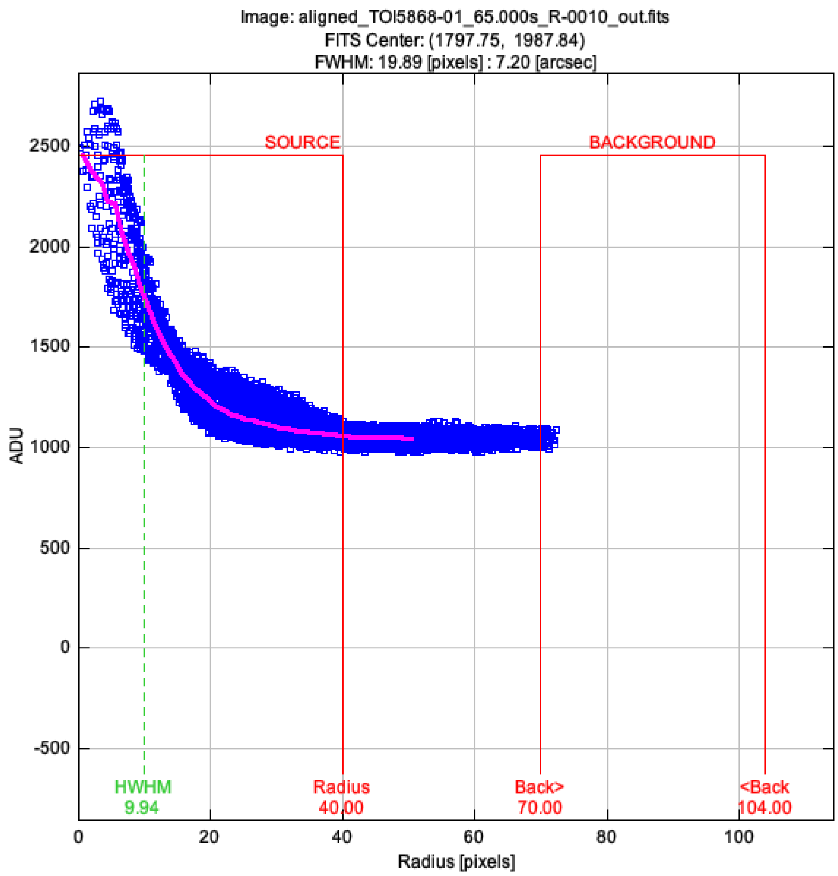


**Figure 1:** Seeing profile of TOI-5868, which notes the radii.

Then, we performed multi-aperture photometry using 216 Gaia stars from the Gaia database that were within a 2.5 arcminute radius of TOI-5868. Additionally, we also selected 14 reference stars outside the radius (**Figure 2**) for reference. Reference stars were selected on the basis of having similar brightness and size as TOI-5868, however, as there were not many surrounding stars with the same characteristics as the target star, slightly larger stars were chosen, as can be shown by **Figure 2**.

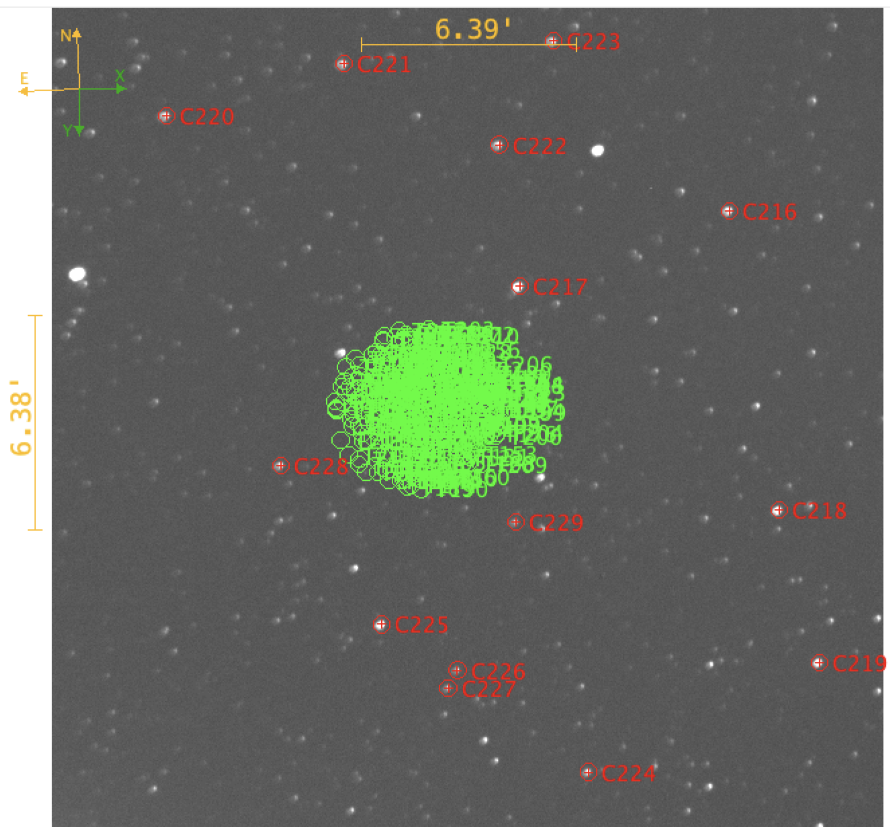


**Figure 2:** TOI-5868 and all 216 Gaia stars (green) within 2.5' of TOI-5868, and 14 reference stars with similar brightness of TOI-5868 (red).

It was then time to generate a light curve. First, we had to open the Data Set 2 Fit Settings window and input the following parameters for TOI-5868: solar radii metallicity, log(g), effective temperature (Teff). All values were previously stated in **Section 2.1**. Additionally, we had to input Linear LD u1 and Quadratic LD u2, whose values were 0.23075209 and 0.34368042, respectively. This is used to calculate the ingress and egress for the transit of TOI-5868.01. The x-data was converted from UTC to BJD and this resulted in a predicted ingress time of 0.621 and a predicted egress time of 0.741.

Next, we had to check if TOI-5868 was a near-eclipsing binary (NEB). According to the dmag-RMS plot, none of the stars—both reference and TOI-5868—were cleared (**Figure 3**). Positions of each data point above the pink and green lines indicate failure to be cleared, including T1, which was our target star. Therefore, this means that TOI-5868 could inhabit an eclipsing binary, but further examination is needed, such as interpreting the light curve.

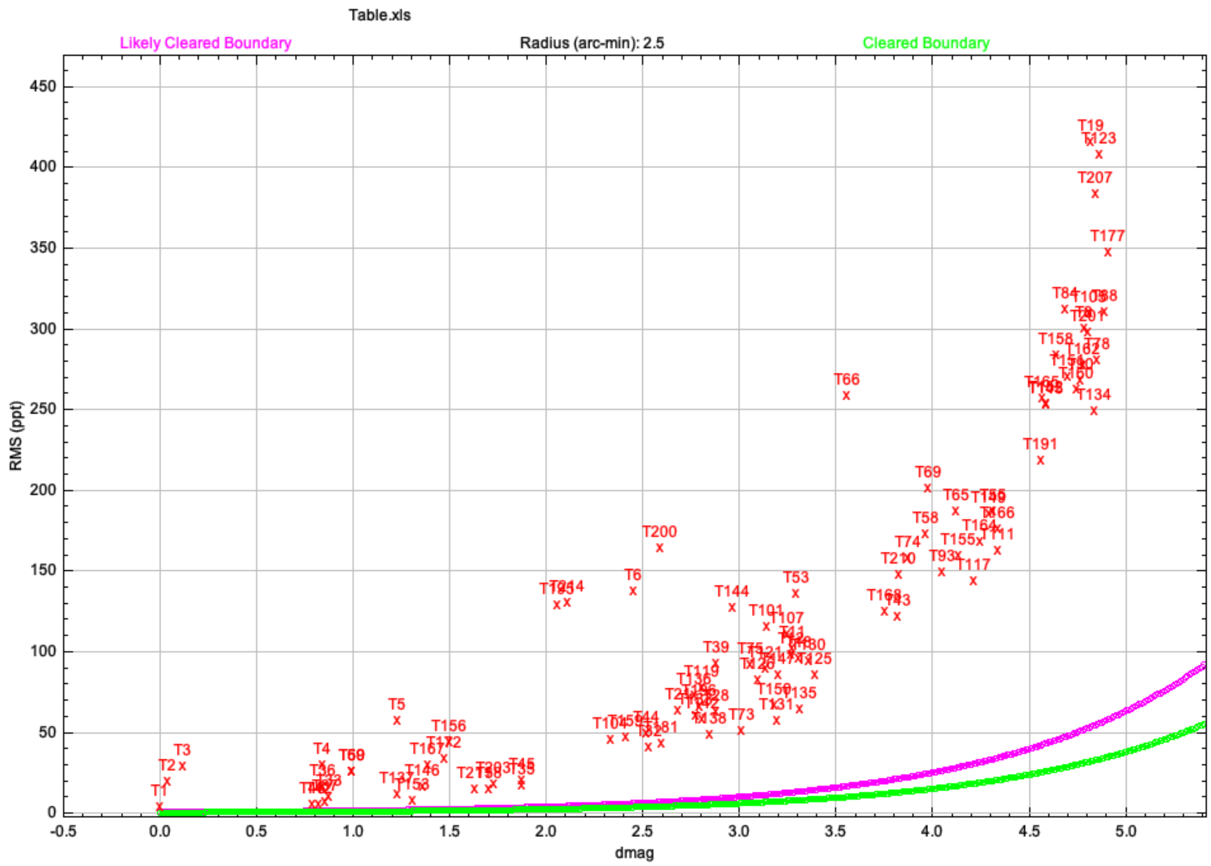


**Figure 3:** dmag-RMS plot to clear potential NEB. T1,the target star, was not cleared.

However, the clear trend in the RMS vs dmag of each of the reference stars indicates that the observations were consistent. The failure of being cleared could be due to the exposure time. If the exposure time was prolonged, and if there were better observing conditions, theoretically, the RMS would decrease, leading for all data points to clear under the green curve.

Finally, it was time to plot the light curve. On the graph, we plotted the flux of TOI-5868, the residuals with error, and the fluxes of three reference stars for comparison. We also enabled Sky/Pixel_T1, Width_T1, AIRMASS, tot_C_cnts, X(FITS), and Y(FITS) on the graph. The previously stated parameters were scaled by 15 and shifted -42, which was according to page 8 of the TFOP SG1 Guidelines.

# Results

In **Section 4.1**, we present our ground-based light curve from the analysis previously stated. In **Section 4.2**, we present some planetary characteristics obtained from the Data Set 2 Fit Settings window from AstroImageJ.

## Plot of Light Curve - 4.1

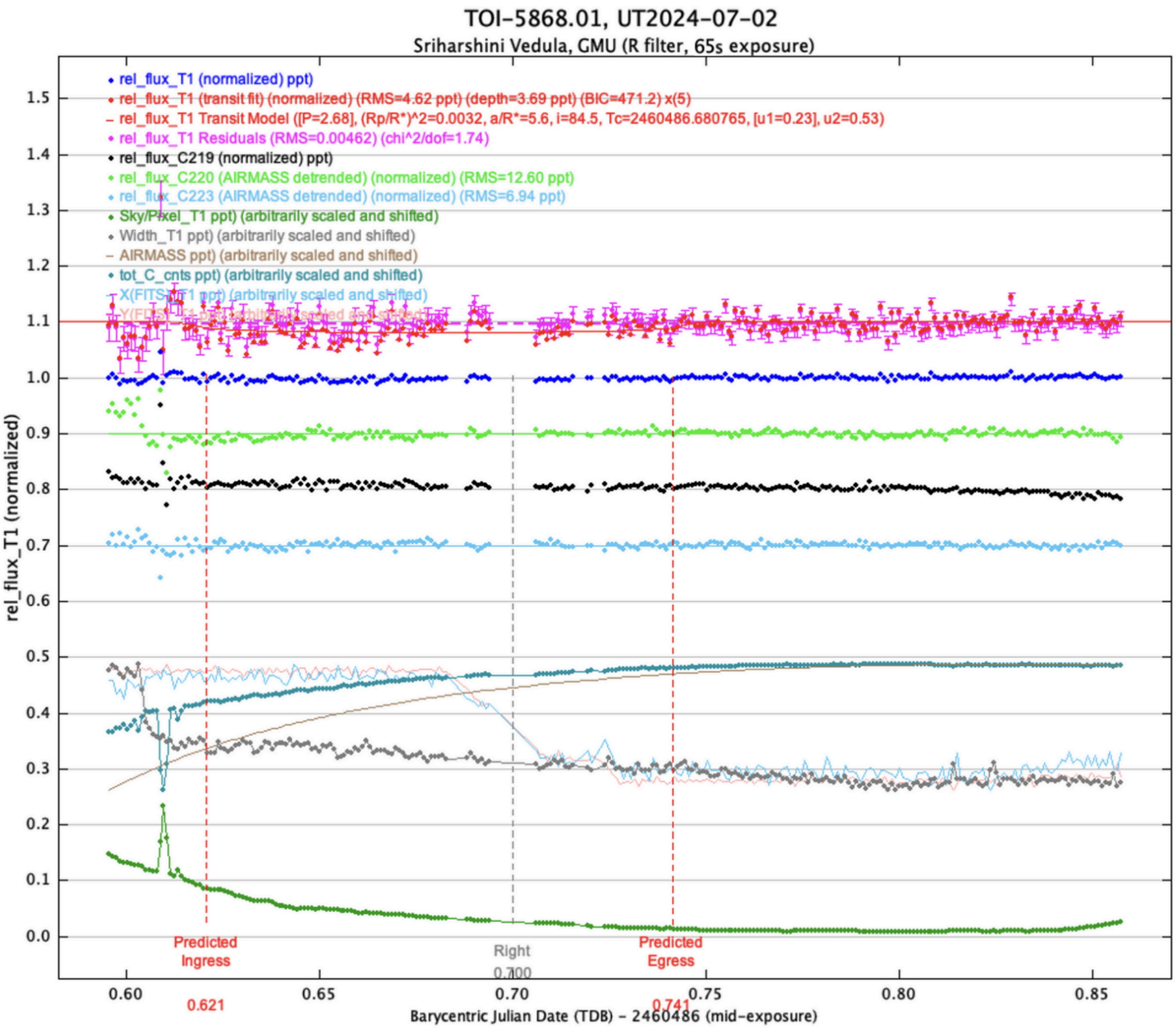


**Figure 4:** Ground-based light curve generated using AstroImageJ.

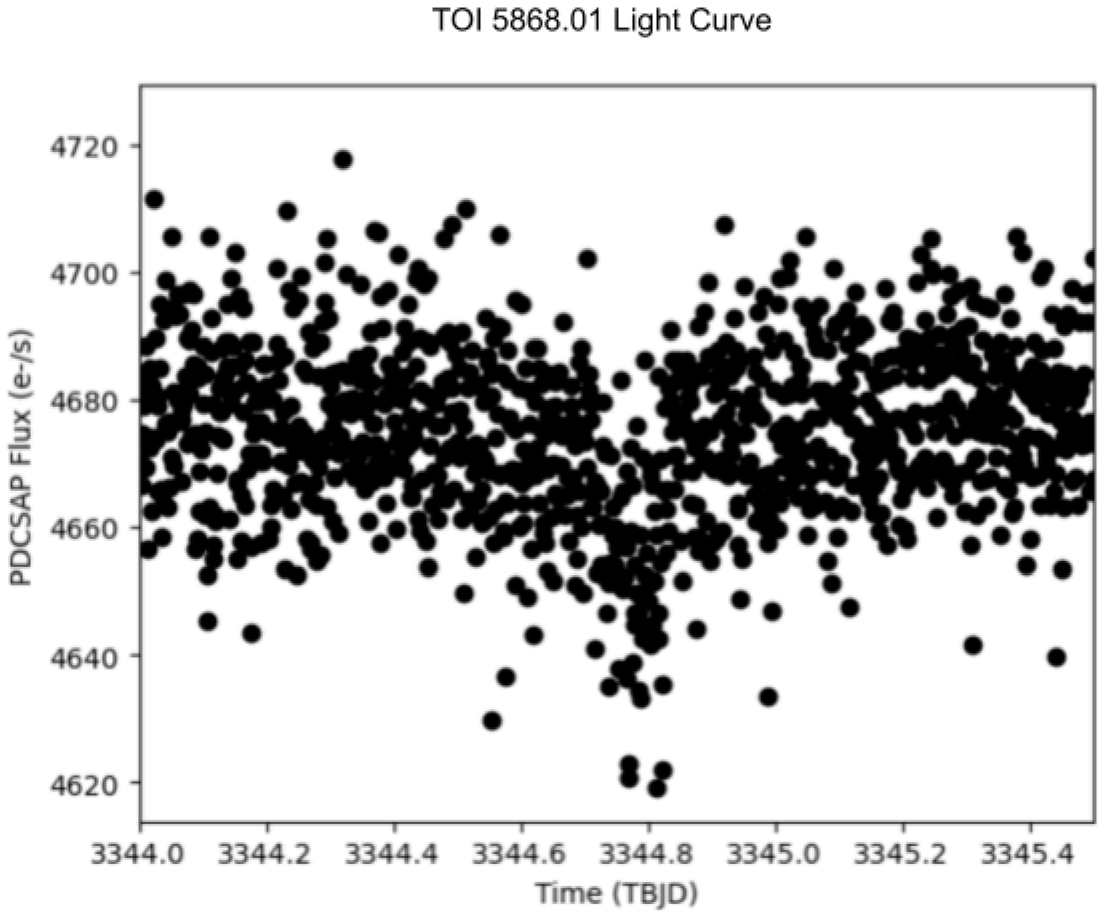


**Figure 5:** Clear transit of TOI 5868.01 generated using Jupyter Notebook.

As shown by **Figure 4**, there is a clear, but very thin transit between the predicted ingress and egress times of 0.621 and 0.741. The transit depth was 3.69 ppt.

To further examine the transits collected by the TESS mission, we generated a light curve using Jupyter Notebook (**Figure 5**). Note that these two figures were generated using two different data sets and that the y-axes depict flux differently.

## Planetary Characteristics - 4.2

Moreover, using the Data Set 2 Fit Settings window, we were given that the transit depth was 0.003245176 using the formula $(\frac{R_p}{R_*})^2$, where $R_p$ is the radius of the planet and $R_*$ is the stellar radius. Using this information, we calculated the radius of the planet to be 0.137 solar radii; this value in earth radii is approximately 14.94, which was achieved by using UnitConverters.net, an online unit converter.

# 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.

## Interpretation - 5.1

We were able to confirm the planetary nature of TOI-5868.01 as the transit's actual ingress and egress times almost perfectly visually matched the predictions. Furthermore, the acquired transit depth, 3.69 is roughly similar to the predicted transit depth of 3.30, further confirming that there truly is an exoplanet.

Additionally, with a relatively short orbital period of 2.68 days, an equilibrium temperature of 1817 K, and a planetary radius of 14.94 earth radii, this exoplanet exhibits characteristics of a Hot Jupiter (Tanner, 2023). Typically, Hot Jupiters have an equilibrium temperature of approximately 1500 K, and the equilibrium temperature of TOI-5868.01 being higher than this further supports its classification of being a Hot Jupiter.

However, we obtained a chi^2/dof value of 1.745. The large distance from 1 suggests that the model does not provide an accurate fit of the data.

## Results in the Context of the Greater Field - 5.2

These findings add to the growing list of confirmed exoplanets and also help us enhance our knowledge of gas giants.

# Conclusion and Future Work

With the use of ground-based photometry, we were able to determine that it is highly likely that TOI-5868.01 is an exoplanet. The transit occurred within the predicted ingress and egress times with the predicted depth, which further confirmed its existence. The characteristics observed—such as a short orbital period of 2.68 days, a planetary equilibrium temperature of 1817 K, and a planetary radius of 14.94 Earth radii—potentially classifies TOI-5868.01 as a Hot Jupiter.

However, the conclusions and interpretations previously stated should be revisited or refined with additional observations and a more comprehensive, accurate model as the high chi^2/dof value indicates the model used was not an accurate fit for the data. In addition, we failed to clear any of the target or reference stars during NEB-analysis. We encourage the use of a more comprehensive check for NEBs that would lead to more conclusive results. We also failed to check if TOI-5868.01 was a false positive. Hence, we recommend that future works include this verification step for confirming the planetary nature of TOI-5868.01. Finally, further analyses could be conducted to explore the physical properties of TOI-5868.01 and verify whether it is a Hot Jupiter or not using applications such as ExoFAST that allow one to impose more detrending parameters.

## References


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