Ground-Based Follow-Up Light Curve Observations of TESS Object of Interest TOI-5868.01

Brandon L. Lee[1], Dr. Peter P. Plavcan[2]

1. Diamond Bar High School, Diamond Bar, CA
2. Department of Physics and Astronomy, 440 University Drive MS 3F3, George Mason University, Fairfax, VA 22030

Abstract

Here we present the discovery and validation of a hot Jupiter around a mid F-type star TOI-5868.01, with a radius of 2.41±0.12 R☉ (R_sun) and an orbital period of 2.6 days, using a combination of Transiting Exoplanets Survey Satellite (TESS) and follow-up ground base telescope at George Mason University. To achieve this, extraction and analysis of the raw data collected by the GMU Observatory were processed through plate solving and detrended using AstroImageJ. The light curve data were used to determine the stellar parameters and the exoplanet data. Our research strongly suggests that TOI-5868.01 can potentially be classified as a hot Jupiter with a short orbital period around a rather large F5 star and is an interesting candidate for atmospheric spectroscopy with JWST.

1. Introduction

An exoplanet is defined as any planet that does not reside within our Solar System (3). As of 2024, there are over 7200 exoplanet candidates that have been discovered by NASA's Transiting Exoplanet Survey Satellite (TESS) alone, 543 of which have been officially confirmed as real exoplanets (1). The TESS mission originally started with financial backing from multiple private companies in 2006, including Google, the Kavli Foundation, and funders from Massachusetts Institute of technology (MIT) (2). Over a half decade later in 2013, NASA approved it as an Explorer Class Mission, finally being launched in April of 2018. This marked the start of a new generation of worlds waiting to be discovered, replacing the Kepler Space Telescope that had been decommissioned in 2013. The TESS Misson's main goal was to "refine" our search for life outside of our solar system, specifically searching for Earth-size worlds orbiting a host star (4). Exoplanets are classified into several different types, most commonly including hot Jupiters, Neptunians, and super-Earths. To find these exoplanets, TESS divides the sky into 26 sectors that are each 24 degrees by 96 degrees across, covering each strip for 27 days and nights (5). Using its four identical, optimized, wide-field cameras, TESS looks for periodic dips in a star's brightness (4). This technique is also known as transit photometry, where a planet passes between its host star and the observer.

Following the identification of an exoplanet candidate, astronomers still need to perform ground-based observations to verify and further elaborate upon the data collected in order to confirm the existence of these exoplanets or root out false positives. In depth analysis is needed to check the potential candidates identified with TESS using higher-resolution imagery, separating out the signals between our presumed target and its nearby neighbors to identify the correct source of the signal, and at the same, refine the measurements of the transit depth, duration, and timing. This method of verifying planets dates all the way back to 1999 when two teams led by David Charbonneau and Gregory W. Henry confirmed HD 209458b as an exoplanet after it had been identified as a candidate using the transiting method (6). Years later, this same method is still being used to identify and confirm possible running candidates. *14 New Light Curves and an Updated Ephemeris for the Hot Jupiter HAT-P-54 b*, written by researchers from Arizona State University and California Institute of Technology, was focused on obtaining 49 datasets to update HAT-P-54 b's Ephemeris, improving the mid-transit uncertainty by 70.27% (Hewitt et al. 2024). This process was conducted using EXOTIC and python in order to reduce the data, creating the 14 new transiting light curves for the Hot Jupiter exoplanet. Similarly, we will be using Python however, we will be using AstroImageJ in place of EXOTIC.

In this paper, we presented follow-up observations of TOI-5868.01. This exoplanet was initially discovered in 2022 orbiting a host star of roughly 2.4 times the radius and 1.49 times the mass of our sun about 2468.42 light years away (6). Its orbital period is 2.68 days with a transit duration of approximately 2.885± 0.286 hours and a predicted depth of 3.1 parsecs per thousand (ppt) (7). Using the GMU Observatory 32" Ritchey-Chretien Telescope with a SBIG 168803 visible CDD, raw science images were collected for further interpretation and analysis. The goals of the paper are to match the depth to the NASA Exoplanet Archive and achieve the lowest Root Mean Squared [RMS] value as possible while achieving a Chi-squared per degree of freedom [chi^2/dof] value as close to the value of one as possible. Finally, we determined and verified the planet radius [R_Earth] to identify the classification of the exoplanet, matching it to the NASA Exoplanet Archive. All of the goals we are aiming for are to hopefully lower the chances of our exoplanet being considered a false positive.

In section 2, we presented our Observations from TESS and the George Mason University 0.8m telescope. In Section 3, we presented our analysis of the TESS light curve for TOI-5868.01 and our ground-based light curve analysis. In Section 4, we presented our light curve results. In section 5 we discussed our results and in Section 6 we presented our conclusions and future work.

2. Observations

In Section 2.1, we presented the TESS Object of Interest 5868.01, detailing its exoplanet candidate properties and host star characteristics as derived from the TESS Input Catalog, the Gaia mission, and other archival sources. In Section 2.2 we presented the TESS sector light curve(s). In 2.3, we presented a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1 Exoplanet and Host Star Properties

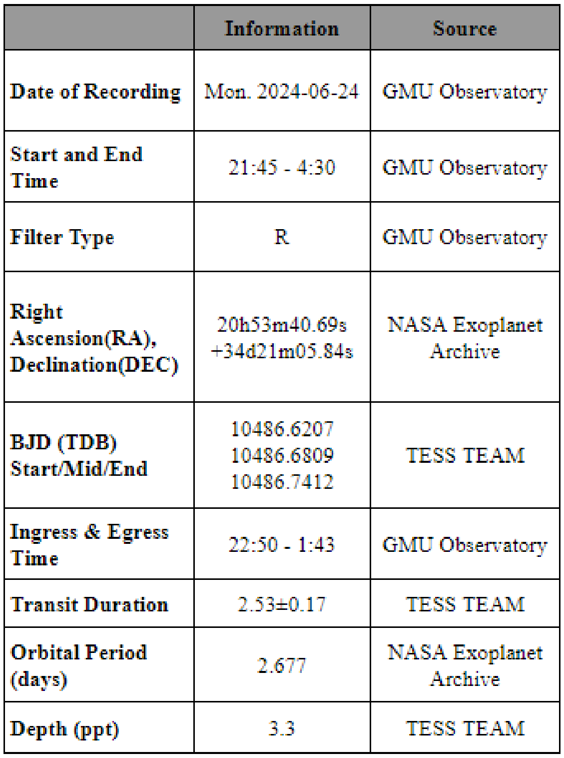
Exoplanet candidate TOI-5868.01's data was originally recorded on November 8th, 2022 and later modified on December 25, 2023 with the TESS Input Catalog ID of TIC 236158940 (7). Our target has an Right Ascension (RA) of 20h53m40.69s and a Declination (DEC) of +34d21m05.84s with an orbital period of 2.677573±0.000018 days. The transit duration is approximately 2.8862.885±0.286 hours and has a planet transit midpoint [BJD] of 2459817.28767±0.0018336. Additionally, the planet transit depth is 3310±131.317 ppm. Finally, our exoplanet has a Planet Radius 14.02±0.77 times the size of Earth with an equilibrium temperature of 1817 Kelvin.

In addition to the Exoplanet properties, we are also given the host star data as listed in the Exoplanet Archive. The required Stellar parameters needed include a stellar distance [pc] of 756.82 parsecs, an effective temperature of 6875.8 Kelvin, and a stellar radius [R_Sun] of 2.41 times the size of our sun.

Besides NASA's Exoplanet Archive data, we are also given the TESS Team data by Swarthmore's Exoplanet Transit calculator at a given location and time (8). In this case, our location was the GMU Observatory at a longitude of 38.8282° N and a latitude of 77.3053° W. With our compiled recorded Exoplanet and Host Star data provided by the TESS team and NASA Archive in ***Table 1***, we can begin our own data observations and analysis explained in section 2.2.

2.2 GMU Cataloged Observational Data

Following the original discovery and data transcription of TOI-5868.01, we used the George Mason University Observatory 32" Ritchey-Chretien Telescope to perform a follow-up validation observation to further investigate the exoplanet's existence. 280 Science exposures were taken using an R filter on June 24th, 2024 with an RA of 20:53:40:69 and a DEC of 34:21:05:84. The observation began at 21:45 UTC and ended at 4:30 UTC, recording an Ingress and Egress of 22:50 and 1:43, respectively. The recorded Visual Magnitude [Vmag] was 11.7.



	Information	Source
Date of Recording	Mon. 2024-06-24	GMU Observatory
Start and End Time	21:45 - 4:30	GMU Observatory
Filter Type	R	GMU Observatory
Right Ascension(RA), Declination(DEC)	20h53m40.69s +34d21m05.84s	NASA Exoplanet Archive
BJD (TDB) Start/Mid/End	10486.6207 10486.6809 10486.7412	TESS TEAM
Ingress & Egress Time	22:50 - 1:43	GMU Observatory
Transit Duration	2.53±0.17	TESS TEAM
Orbital Period (days)	2.677	NASA Exoplanet Archive
Depth (ppt)	3.3	TESS TEAM

Table 1: Principle Data on TOI-5868.01

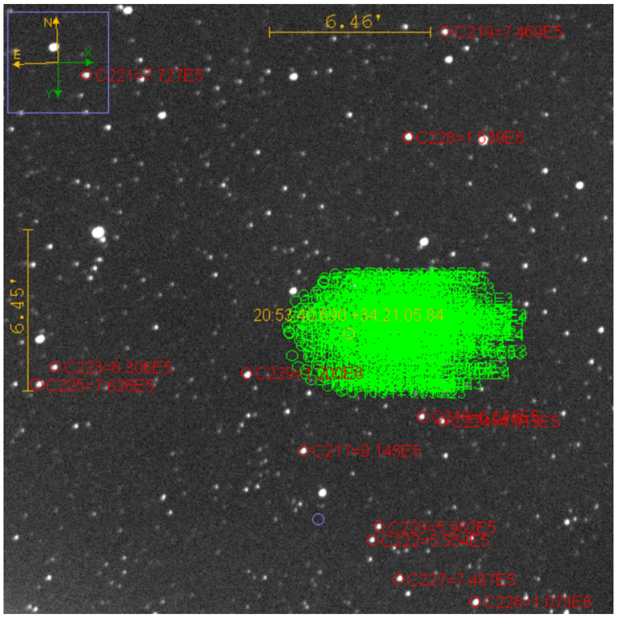


Figure 1: Multi-Aperture Photometry Field Image (yellow annotation is our T1)

3. Analysis

In Section 3.1 we presented our tools used to create and analyze the data for light curve modeling. In section 3.2 we reviewed the process of data reduction. In section 3.3 we discuss the plate solving and aligning of our images. In section 3.4, imported the virtual stack images and created a seeing profile. In section 3.5, we examined the process of performing multi-aperture photometry and generating a measurements table file. In section 3.6, we discussed the process of light curve modeling. Finally, in section 3.7, we presented the process of performing a NEB analysis. The procedure was completed with the assistance of a comprehensive guide by Dr. Peter P. Plavcan et al called the *Campus Telescope TESS Follow-up Light Curve Tutorial* (11). Other sources referred to during this process was the *TFOP SG1 Guidelines v6.4* (12) and the *SCHAR Campus Telescope Data Analysis w/ alnitak tutorial v2021*, also made by Dr. Peter P. Plavcan et al (13).

3.1 Analytical Tool Set

The programs and applications we used include AstroImageJ and Python. AstroImageJ is an all-in-one software for image calibration, differential photometry, and exoplanet modeling. It can also be considered the standard for any exoplanet analysis and modeling for professional and amateur astronomers (14). Python is a rather well known general-purpose programming language that can be used for web applications, software development, data science, etc. However, for this purpose we used it to install Alnitak to plate-solve our raw science images.

3.2 Data Reduction

The GMU Observatory took 20 darks, 10 flats, and 280 science images as .fits files. 10 of the darks and the 10 flats taken at a 3.0 second exposure time. The other 10 darks and the 280 science images were taken with a 65.0 second exposure time. The first step in reducing our images was creating a median combination of darks of the same exposure times to create two master darks files. The main purpose of this was to reject cosmic rays and reduce the noise by a scale factor of 3. The second step would be to create a master flatfield by combining the 10 flat images with one of our master darks of the same exposure. This removes the electronic detector signal, isolating the electrons generated by photons. Finally, to create our reduced science images, we combine the master dark of 65.0 seconds with our master flat and the 280 raw science images. This final step is to remove the variation in individualized pixels to allow the pixels that behave differently report the same number of counts and photons.

3.3 Image Plate Solving and Aligning

Before plate solving and aligning our now data-reduced images, we first needed to inspect all images that may have large noticeable jumps or space satellites passing by. Out of the 280 images, 24 were manually removed. Normally, we could've utilized AstroImageJ and a nova.astrometry.net API key to solve our images, assigning each of the objects in every single frame Right Ascension (RA) and Declination (DEC) coordinates. Plate solving not only allows us to identify our targeted star but also distinguish other reference stars which will be needed later on in sections 3.4 and 3.5. If the images are not plate solved, they would have to be aligned. The process of image alignment corrects and normalizes tilt series images, aligning and matching them to a common rotational axis. Unfortunately, we ran into an unexpected error which caused the plate solving process to fail or to completely time out, giving us back the same raw science images.

To navigate around this issue, we decided to use Python and Alnitak to solve our images. The necessary files were downloaded from github (15) and other dependency programs like Astropy, Matplotlib, etc were manually installed using pip. An API key was obtained from nova.astrometry.net, similarly to how we would've done it with AstroImageJ. This key will go into the config.json file that was downloaded earlier using a line of code input into python. In order to prevent any errors before actually running Alnitak, we ensured the darks and flats were capitalized in their own separate directories, and they were inside the directory that contains the raw science images. The final step was to command python to run Alnitak by inputting a line of code, stating the directory location of our .fits images. All good images were placed in a "reduced" folder and any images the program considers an unsatisfactory image will be placed in a "bad" folder. In this case, Alnitak removed 9 out of the 256 images, reducing our final number of images to 247.

3.4 Virtual Stack and Seeing Profile

Our next step is to import a virtual stack of our data-reduced and platesolved images into AJJ and identify our target star (T1) to create a seeing profile. Right after importing our virtual stack, we first needed to find our star by inputting the RA and DEC coordinates into the top header of our virtual stack images, producing a yellow aperture surrounding our T1. Now, to align our images, we used the "Align stack using WCS or apertures" feature in the process tab, putting them into a separate directory. To allow the align process to occur correctly, 3 or more reference stars would be needed besides our T1 star. Afterwards, we constructed a Seeing Profile shown in ***Figure 2*** to obtain our radius of 34 for our aperture size along with 59 and 89 as our background's inner and outer radii for the annulus sizes. The aperture and annulus sizes would then be input into the Aperture Photometry Settings, allowing us to get ready to perform our multi-aperture photometry.

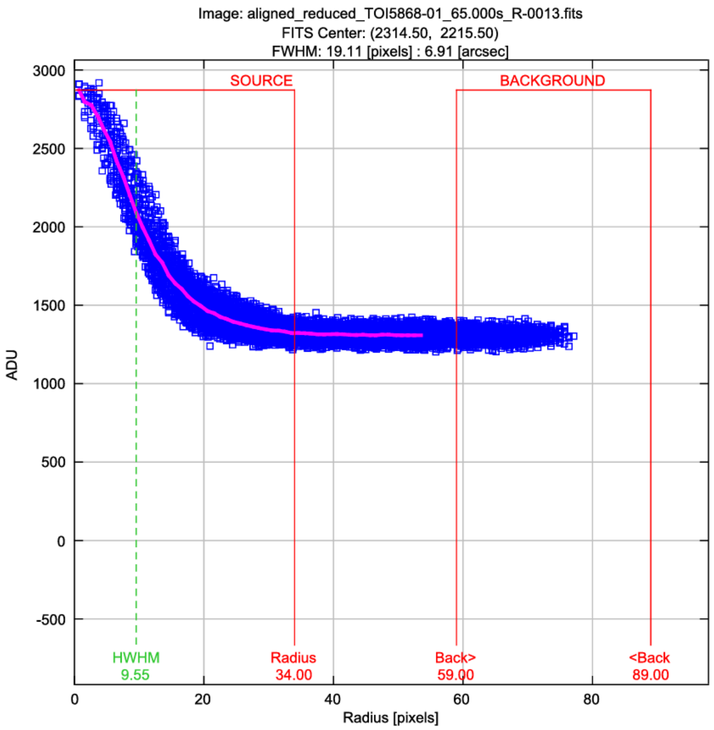


Figure 2: Seeing Profile

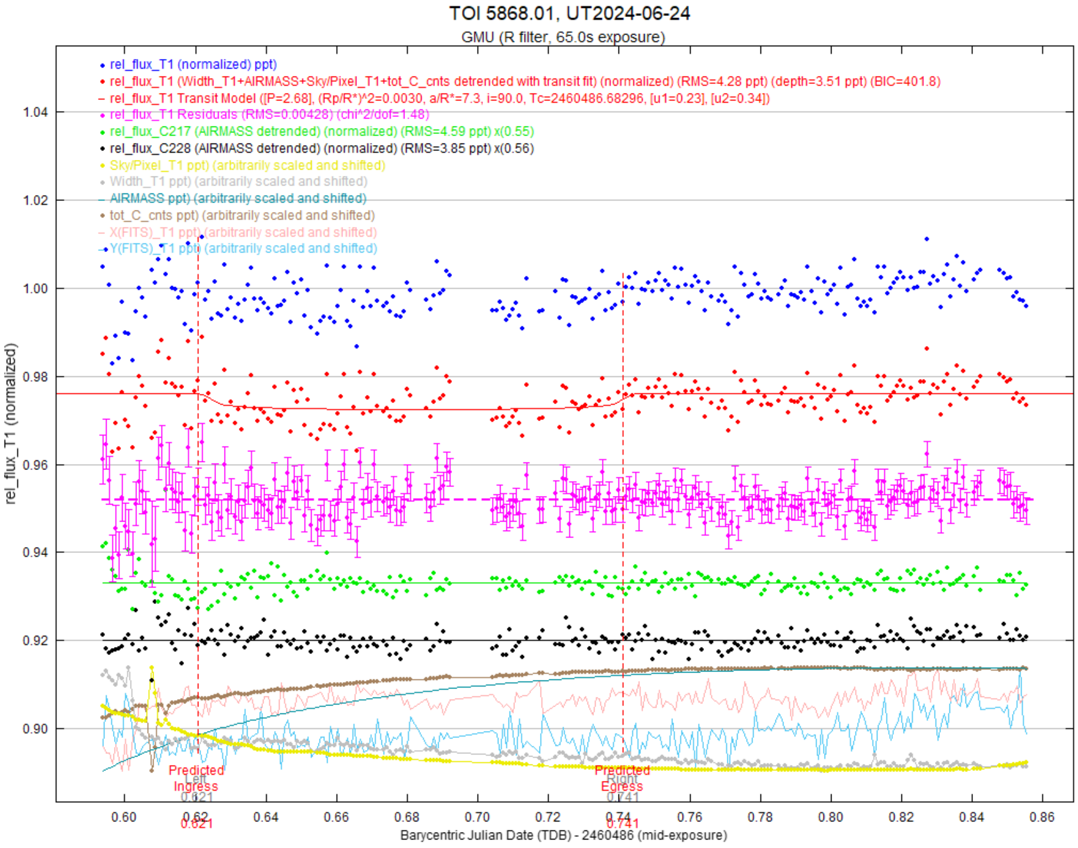


Figure 3: AJJ Light Curve generation

3.5 Multi-Aperture Photometry and Measurement Table

Aperture photometry is the process of focusing on purely measuring the amount of flux coming from a single star using a circular aperture. Before we perform the aperture photometry, we must first import our Gaia Stars .radec file into the image sequencing virtual stack. These reference stars usually show up within a 2.5 arcminute radius of our T1 star and will be used later on in our NEB plot in section 3.7. In the Multi-Aperture Measurements settings, we used RA/DEC to locate the aperture positions and used 12 auto-comparison stars that are chosen by AstroImageJ along with our 215 previous Gaia stars to place our apertures. Usually, we only need 10 comparison stars that have similar size and brightness to our target star, but we ended up using 13 comparison stars. The final resulting Aperture Photometry field of view image is displayed in ***Figure 1.*** After performing the Multi-Aperture Photometry, we created a Measurements .tbl file which is essential for modeling a light curve plot in our next section.

3.6 Light Curve Modeling

When beginning the light curve modeling analysis, we use a .plotcfg template file from *Exoplanet Observing by Amateur Astronomers* (16) to revert all plotting windows to proper settings. This ensured our analysis is in compliance with TESS/K2 guidelines. In AstroImageJ, there are three main panels used to manipulate the data shown in the light curve when plotted. In our Multi-plot Main window, we first needed to set "Default X-data" to the Barycentric Julian Date with Barycentric Dynamical Time. This refers to our plot to the Solar system Barycenter (center of mass) and takes relativity into account since our atomic clocks change rates (17). In the "V. Marker 1" and "V. Marker 2" boxes, we would input our predicted ingress (0.6207) and egress (0.7412) times shown in ***Table 1***. We then used auto-arrange for our X-Axis Scaling to make our data automatically visible in our plot. For now, the "Fits and Normalize Region Selection" would be the same as our Ingress and Egress predictions.

In our "Data Set 2 Fit Settings" panel, we first need to obtain the necessary data to fill out the panel from the ExoFOP databases (18). This included our target's "Orbital Parameters" and "Host Sar Parameters". The value input into "Orbital Parameters" is just the orbital period of our exoplanet which was 2.68 days. As for the host star parameters, we needed the stellar radius of 2.41 times our sun, an effective temperature [Teff (K)] of 6875.79, a metallicity [Fe/H] of 0.067, and the surface gravity of 3.8487. Using these values, we input them into EXOFAST's Quadratic Limb Darkening calculator giving us the back values of 0.23075209 and 0.34368042 to put into the "Linear LD u1" and "Quad LD u2" boxes. Finally, we temporarily uncheck all detrending parameters and display our Residuals and Error bars on our plot.

The third and final panel, "Multi-plot Y-data", is used for purely manipulating the 11 plots shown in ***Figure 3***. The first in blue is our normalized "rel_flux_T1" plot without any determining parameters and showed no sign of a transit because of certain dilutions and external factors. Which is why, in our second plot in red has a few detrending parameters including Width_T1, AIRMASS, Sky/Pixel_T1, and tot_C_cnts to lower our Bayesian Information Criterion (BIC) and our Root Mean Square (RMS) values. Generally, the lower we can bring these values, the more accurate we can consider our data to fit our transit model. In order to better see this plot, we stretched the Y-axis of our graph until all of our data fit between around a 0.1 range, making the transit much more visible. Besides our T1 graphs, we also added two comparison star graphs with the AIR MASS detrending parameter on them and a few detrending parameter graphs, including Width_T1, AIRMASS, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1.

3.7 Nearby Eclipsing Binary Analysis

Our final step in analyzing our reduced images and data is checking the neighboring stars to see if they've been clear or not as a Nearby Eclipsing Binary (NEB). NEBs systems contain two stars orbiting their center of gravity, resulting in a false positive exoplanet candidate. This is because, from our perspective, the NEB analysis light curve would pick up a dip in light flux, signaling a transit. In actuality, it is a decrease in brightness when one star in the binary system passes in front of the other. In our 2.5 arcminute radius, 215 Gaia stars were referenced. If any of them cleared the NEB test, our aperture would be considered contaminated because of extra flux from other stars manipulating our lightcurve data. These cleared NEBs are now considered outliers and must be removed to preserve the T1 light curve, limiting the change in flux to only our targeted star. Out of 215 Gaia stars from the .radec file, 119 were not cleared because the flux was too low and the other 96 had a NEBdepth RMS value lower than 3. Since we did not have any outlier reference stars, we didn't remove any selected target stars because they didn't affect our light curve. Our final NEB plot is shown in ***Figure 4***.

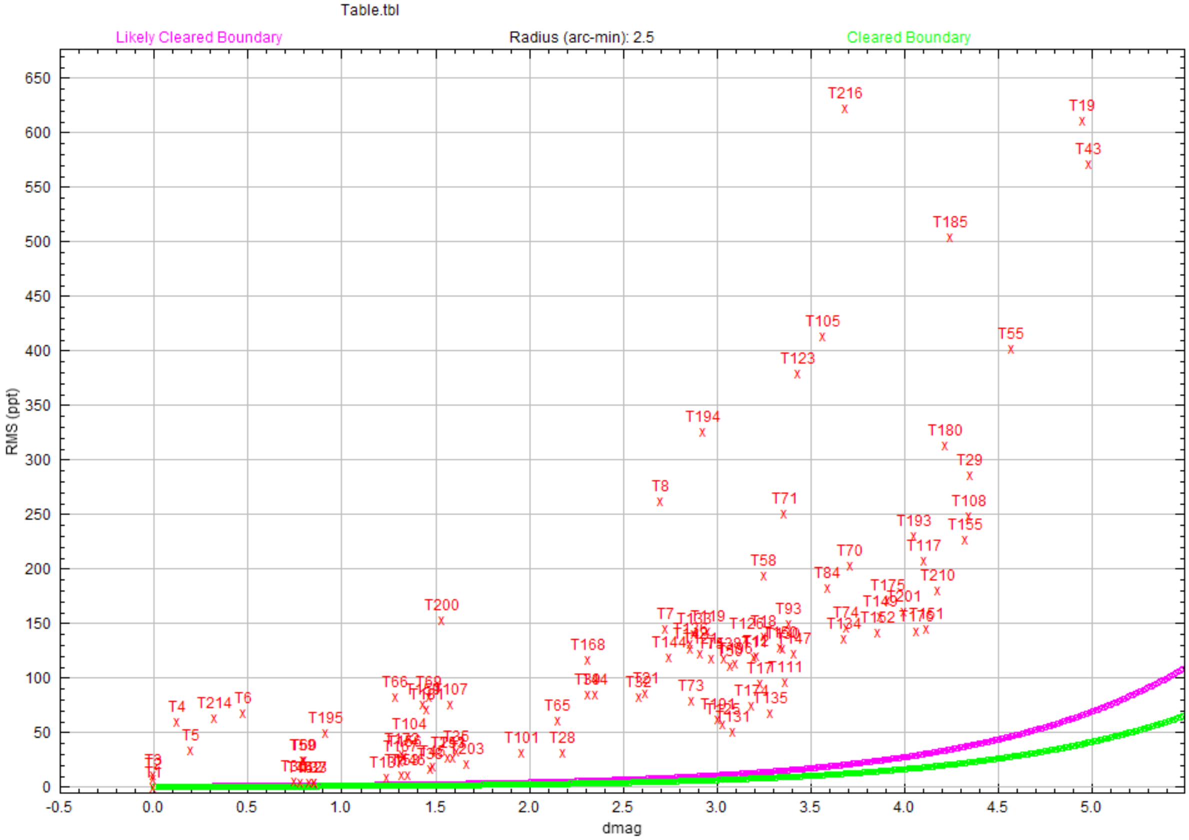


Figure 4: AJJ NEB Analysis Plot

4. Results

In this section, we presented our results from the light curve transit modeling. Light curve plot showed convincing evidence of transit occuring (fig 3). The gap in data plot refers to cloud cover during that time period. The flux plot of T1 was generated by AstroimageJ and detrended using the AIRMASS parameter and the flux of nearby stars (fig 1). The flux plot shows a transit model that follows close to the predicted ingress and egress times, 0.021 and 0.741 respectively. The curvature showed a transit depth of 3.51ppt. The RMS is 4.20ppt and the chi square/ degrees of freedom is 1.48. Our P value for transit model is 2.68. Although the NEB plot indicates that all reference stars passed the analysis, the results were considered inconclusive. We cannot be entirely certain that the planet is not a false positive due to potential disruptive factors and errors. Errors in our results were as follows: cloud cover during data recording; random flux caused by detector noise, random sky noise, and random sky glow. The Rp/R value is 0.0030. The stellar radius is 2.41±0.12. Stellar Temperature of 6875±104.8. The exoplanet radius is estimated to be 1.29 times the size of Jupiter (R_Jup) or 14.19 times the size of earth (R_Earth).

5. Discussion

To verify if TOI-5868.01 is an exoplanet, we performed statistical analysis on data provided by the light curve. For our data to approximate close to what we expect, the chi square per degrees of freedom is close to the value of 1.

$$X_v^2 = \frac{X^2}{V}$$

Equation 1: Chi-square per Degree of Freedom

Given ***Equation 1***, AstroImageJ calculates our result to be 1.48 which is within acceptable parameters. This means the flux we observed is close to the expected values. Therefore, we have convincing evidence of the existence of an exoplanet. We also can classify the type of exoplanet. From the ratio of Rp/R, the fractional decrease in detected light is 0.0030. From ***Equation 2***, we have calculated the radius of the planet to be 14.19 R⊕.

$$\text{transit depth} = \frac{R_\text{p}^2}{R_\text{star}^2} = \left(\frac{R_\text{p}}{R_\text{star}}\right)^2$$

Equation 2: Observable change in flux (ΔF)

This is quite close to the predicted value in exofop.com which was 14.0246±0.769821 R⊕. The radius of Jupiter is approximately 11 times the size of Earth, but our exoplanet is 14 times the size of Earth. This would end up classifying TOI-5868.01 as a "super" hot Jupiter. The stellar type is F5 according to stellar effective temperature. False positive is negligible because the chi square per degrees of freedom is close to 1. Eclipsing binary false positives requires further data collection as there might be a second light curve dip. A longer time in collecting data can confirm or deny the existence of eclipsing binaries. Nearby eclipsing binaries are inconclusive as light curve data are required for each nearby star, and data for those were not processed.

6. Conclusion

TESS located a transit signal of a probable super Jupiter planet orbiting a likely F5 type star TOI 5868 that is 756.82±18.5205 parsecs away. In this study of TOI 5868.01 verification, we have conducted follow up observations using ground based transit photometry. The validated planet has a radius of 14.19 R⊕ and orbital period of 2.6 days. However these are just the first steps in validating the existence of an exoplanet. Further steps and data gathering techniques must be performed, especially data collected by the JWST which can provide resolution infrared spectrographs such as IRD will allow a closer approximation of the planet's mass. Further data analysis can be performed using other softwares like EXOFAST which uses the Differential Evolution Markov Chain Monte Carlo (MCMC) method to characterize parameter uncertainties and covariances, offering fast and robust results. The code can derive stellar parameters alongside transit and radial velocity parameters, providing self-consistent results. Verification of 5868.01 as a super hot Jupiter exoplanet could also be verified through techniques such as Exoplanet atmosphere spectroscopy.

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