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Ground-based light curve follow-up validation observations of TESS object of interest TOI 5868.01

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ABSTRACT

The Transiting Exoplanet Survey Satellite (TESS) mission scans the sky to detect possible exoplanets using the transit photometry method. To verify that candidate exoplanets are in fact real and are not false positives, further ground-based observations are needed. The goal of this paper is to provide a ground-based observation of TESS Object of Interest (TOI) 5868.01 and to confirm or deny the existence of TOI 5868.01. We used the George Mason University 0.8m telescope to observe TOI 5868.01 and AstroImageJ to process the data. We found that the transit of TOI 5868.01 occurred at the expected time, with the expected duration and depth, but we could not conclusively rule out false positives.

1. INTRODUCTION

The study of exoplanets is becoming a more and more important part of astronomy. As of right now, more than 5700 exoplanets have been confirmed. Nearly 75% of these were discovered with the transit method, which detects dips in a star's brightness that happen when a planet passes in front of it [9].

The Transiting Exoplanet Survey Satellite (TESS) mission was launched in 2018 to discover transiting exoplanets by surveying the sky. It has discovered 7021 TESS Objects of Interest (TOIs), 410 of which have been confirmed as exoplanets [11]. The rest of these candidates still await validation.

Part of the validation process is ground-based light curve analysis. Similar studies have been done to confirm other TOIs [5], but none have yet been done on TOI 5868.01. There is thus a need for more follow-up observations on it.

In this paper, we present follow-up observations of TOI 5868.01 using the George Mason University 0.8m telescope. TOI 5868.01 is predicted to be a Hot Jupiter orbiting a sun-like star 700 parsecs from us [8]. Our goal in this paper is to investigate whether or not the transit occurs on the expected star at the expected time, with the expected duration and depth.

2. OBSERVATIONS

In Section 2.1 we present the TESS Object of Interest 5868.01 and its exoplanet candidate and host star properties from the NASA Exoplanet Archive. In Section 2.2 we present the TESS sector light curve. In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1. *Properties of TOI 5868.01*

The TOI 5868 system was first discovered by TESS in 2022. It is located at right ascension 20h53m40.69s and declination +34d21m05.84s, and is 757 parsecs from us. The host star is slightly larger and brighter than the Sun, with a radius of 2.41 solar radii and an effective temperature of 6876 Kelvin. The candidate exoplanet, TOI 5868.01, is thought to be a Hot Jupiter with a radius of 14.02 Earth radii, an orbital period of 2.7 days, and an equilibrium temperature of 1817 Kelvin [8].

2.2. *TESS Light Curve Discussion*

During orbit 157, sector 75, TESS observed TOI 5868.01 using camera 4 and CCD 4 [12]. We obtained the resulting light curve from the Mikulski Archive for Space Telescopes [10] and plotted it in Python using the Astropy package [2].

Figure 1 is the complete light curve, and Figure 2 is one transit zoomed-in. Figure 1 clearly shows transits recurring about once in 3 Barycentric Julian Days. Figure 2 shows a clear transit, about 0.15 Barycentric Julian Days long and 3.3 ppt deep.

2.3. *Our Observations*

We observed TOI 5868.01 on June 24, 2024 on the George Mason University 0.8m telescope with an R filter. We started observing at 21:45 and ended at 4:30 that night, with the transit being from 22:50 to 1:43. We took a total of 280 science images each with an exposure time of 65 seconds. In addition, we took 10 flat images with 3 second exposure, 10 dark images with 3 second exposure, and 10 dark images with 65 second exposure. The first of our images is presented in Figure 3. Unfortunately, exposures 95-99, 107-118, 130-132, and 135-137 were unusable due to streaking, so we put them in a separate folder and excluded them from the analysis.

3. ANALYSIS

In this section, we present our analysis of the observational data using AstroImageJ. We approximately followed the AstroImageJ Cookbook [6] and the TFOP SG1 Observation Guidelines [3]. Section 3.1 describes the process of reducing the data and running aperture photometry. Section 3.2 describes the creation of the light curve.

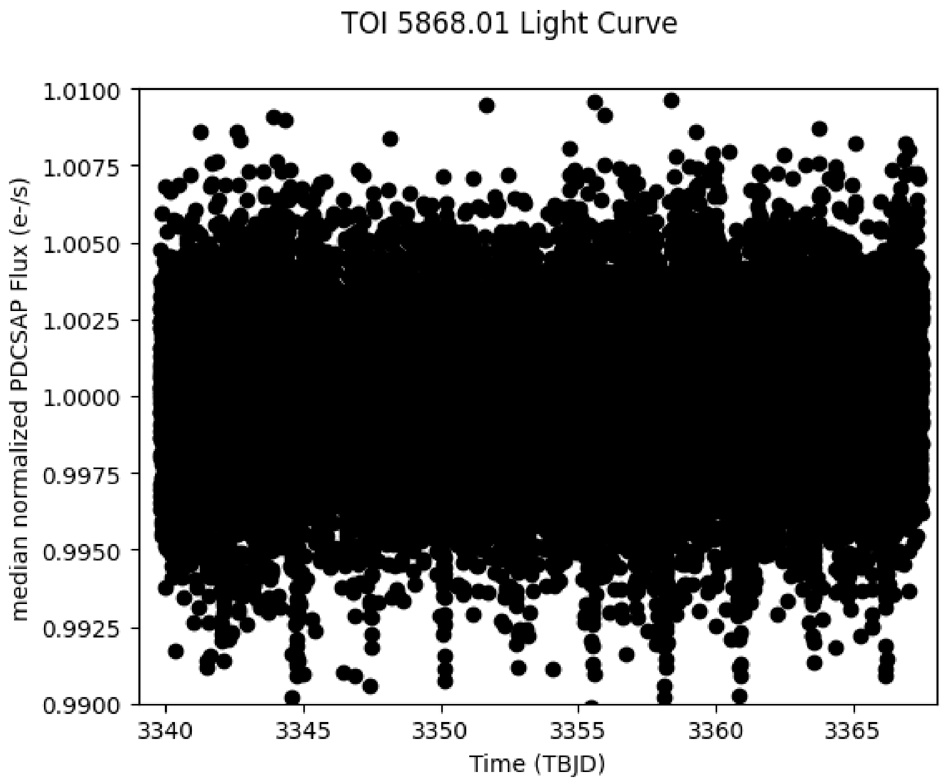

Figure 1. The full light curve from the TESS mission's observation.

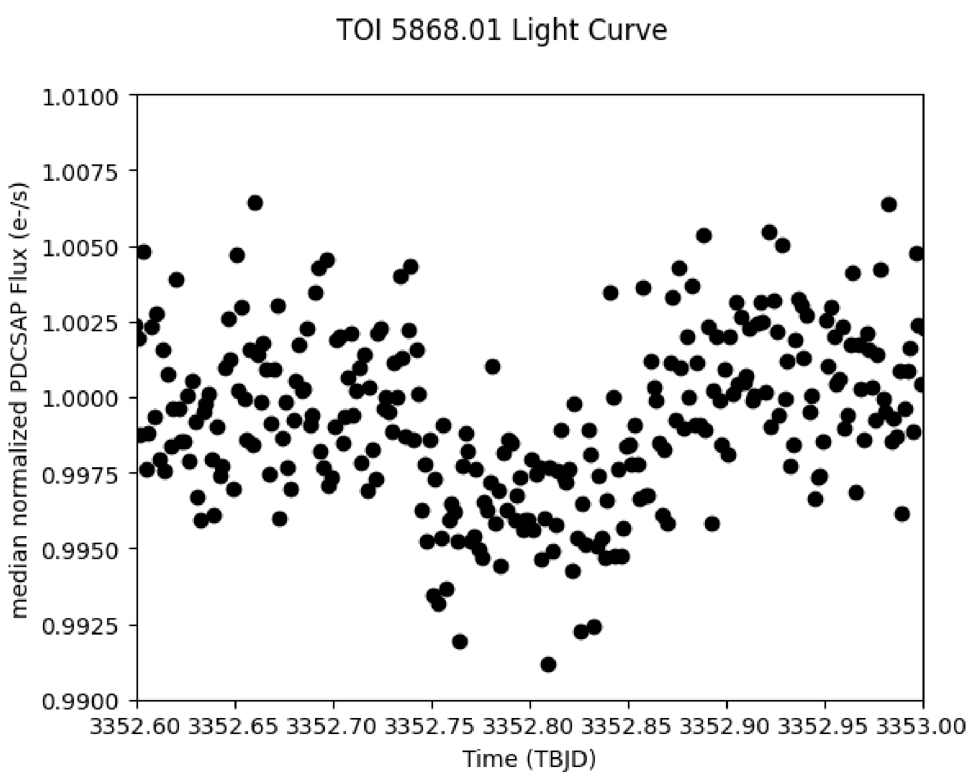

Figure 2. Figure 1, now zoomed in on the portion between 3352.6 and 3353 TBJD. It shows a clear transit.

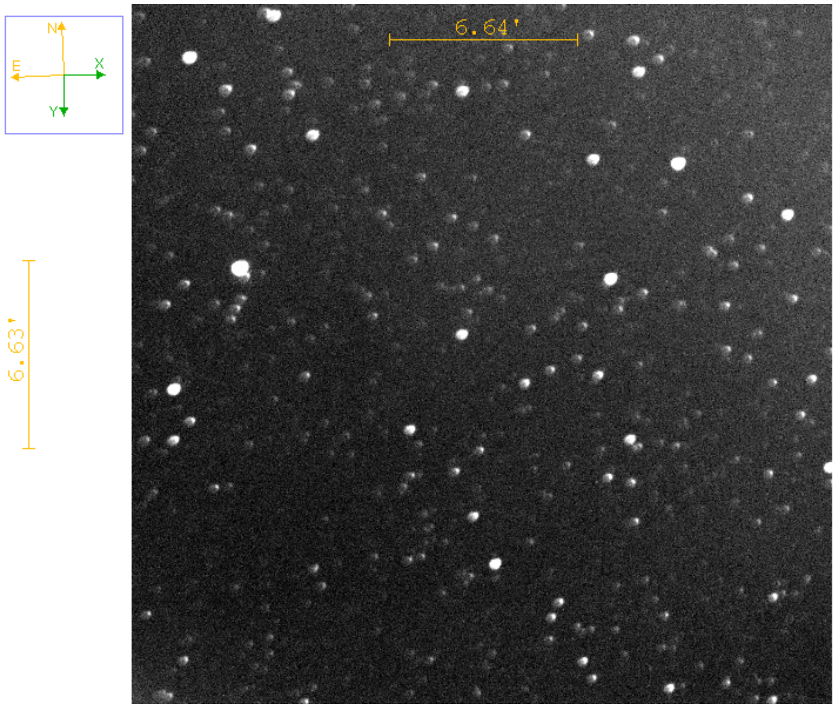

Figure 3. The first of our science images, taken by the GMU Observatory with a red filter and 65s exposure, as displayed by AstroImageJ.

3.1. *Preliminary Data Processing*

We first used AstroImageJ's CCD Data Processor Tool to reduce our data. We subtracted the flats from the darks and created a master flat file, then used the master flat and the science darks to calibrate our science images.

We then set up a local Astrometry.net ansvr server according to [1]. This was used to plate-solve our data so that we could create our light curve.

We used AstroImageJ's Aperture Photometry Tool to generate a seeing profile (Figure 4) from which we determined the size of our annulus which we needed later.

In order to find nearby reference stars and eclipsing binaries, we placed a circle with radius of 2.5 arcminutes around the target star, then retrieved the locations of nearby eclipsing binaries from the Gaia mission at https://www.astro.louisville.edu/cgi-bin/gaia_to_aij/.

We also needed to select some reference stars to calibrate the flux from the target star with the flux from surrounding stars. We let AstroImageJ's Multi-Aperture Photometry Tool place these apertures for us; the results are shown in Figure 5. We were then able to perform the photometry and record the fluxes of all apertures in a table.

3.2. *Light Curve Creation*

Before we created the light curve, we first ran a check using AstroImageJ's NEB Analysis Macro to identify any nearby eclipsing binaries that could have caused a

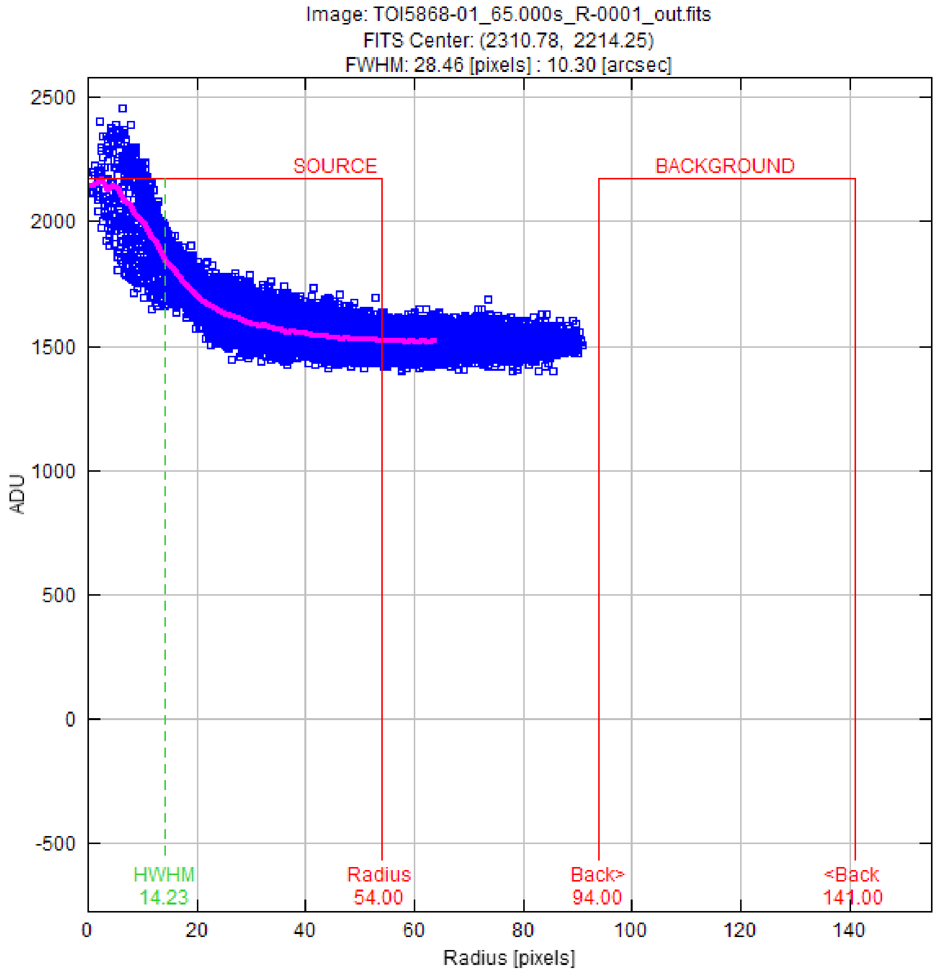

Figure 4. The seeing profile from AstroImageJ. The radius of the object aperture is 54, and the background annulus has inner radii 94 and outer radii 141.

false positive. This generated a report of the likelihood of nearby stars causing a false positive, which is presented in Section 4.

We then used AstroImageJ's MultiPlot tool to plot the light curve of TOI 5868.01. We retrieved host star parameters for TOI 5868.01 from the NASA Exoplanet Archive [8], Eric Jensen's Transit Finder [4], and ExoFAST [7]. In our plot, we also displayed the fluxes of reference stars C217 and C221 to be sure that the transit does not happen among all stars. Moreover, we showed the detrending parameters Sky/Pixel_T1, Width_T1, AIRMASS, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1.

Among these detrending parameters, we found that using Width_T1, which is mean of the X- and Y- direction FWHM of the target, decreased the RMS value by 0.036, while all the other parameters increased the RMS value. Thus, we detrended the data with Width_T1. Figure 6 shows the settings that we used, and our final light curve is presented in Section 4.

4. RESULTS

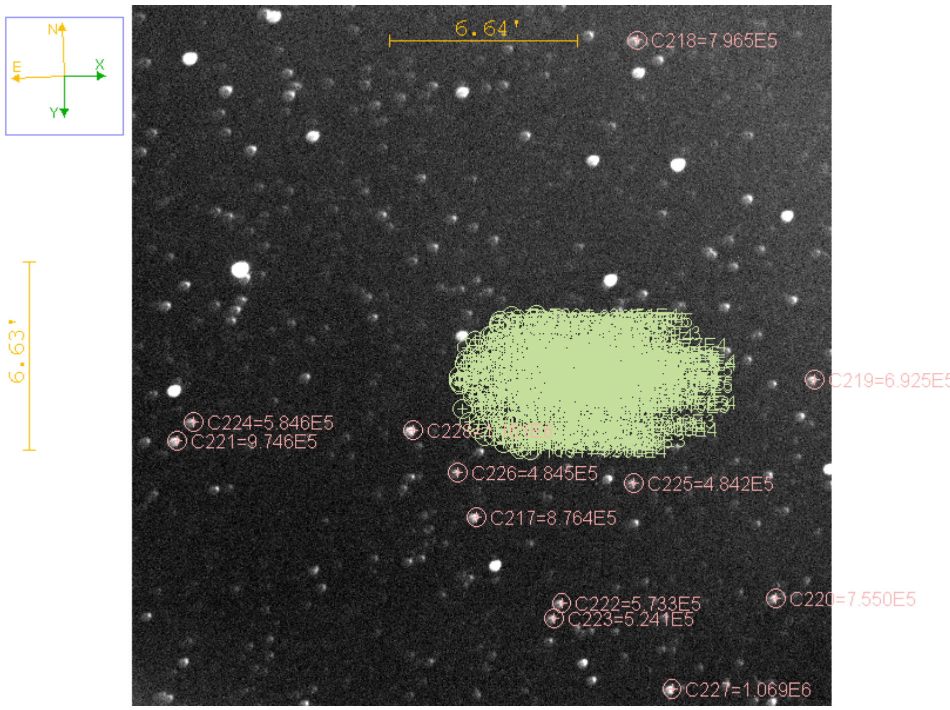

Figure 5. The field of view, with apertures labeled. The green labels are possible NEBs and the red labels are reference stars chosen by AstroImageJ.

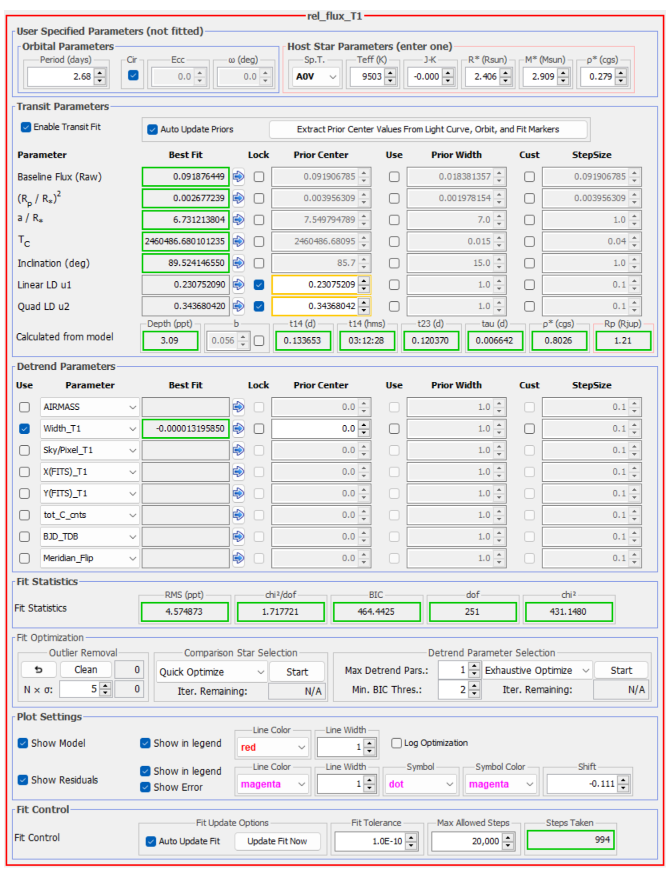

Figure 6. Image showing the settings that we used in AstroImageJ. The values in the "Transit Parameters" section come from the databases mentioned above.

In this section, we present the results of our analysis. Figure 7 is our DMag vs. RMS plot and Figure 8 is our final light curve.

Out of 216 nearby eclipsing binaries, 118 were identified as "Not Cleared-flux too low" and 97 where identified as "Not Cleared". Figure 7 shows a roughly exponential pattern with a wide scatter. None of the stars are below either of the purple or green curves.

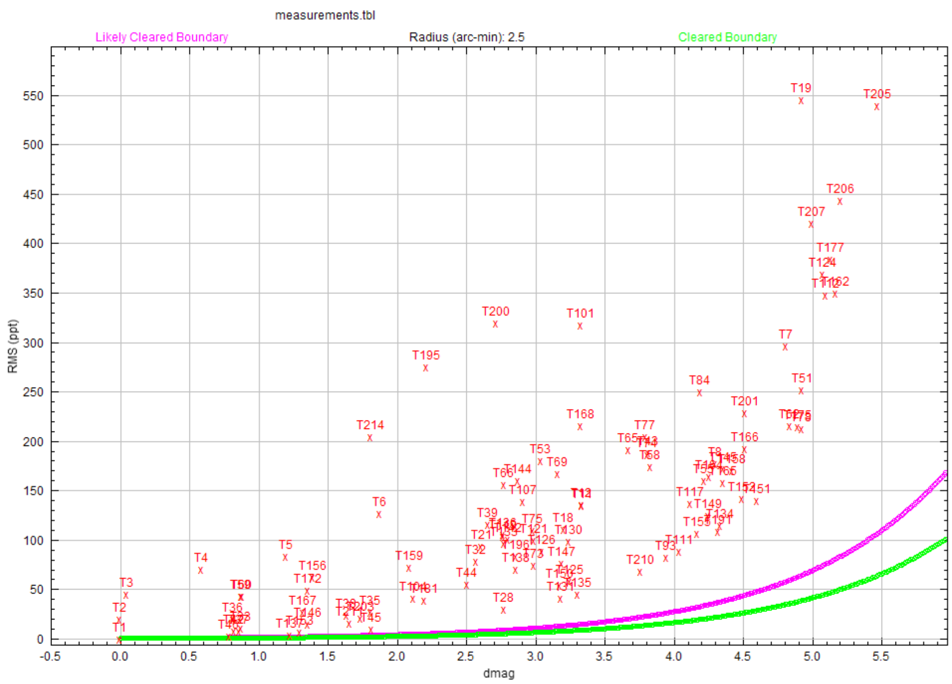

Figure 7. Our DMag vs. RMS plot. No stars were completely cleared, as none of them are beneath the purple or green curves.

Figure 8 shows our final light curve. The top 3 plots are for TOI 5868.01; the blue plot is the original measurements, the red plot includes detrending and the transit model, and the pink plot shows the error bars. The black and green plots show the light curves for reference stars C221 and C217, respectively. At the bottom, our detrending parameters are plotted together.

The Root-Mean-Square of our residuals was 4.57 ppt and the Bayesian Information Criterion was 464.4. Our transit model, using Width_T1 detrending, found a transit depth of 3.09 ppt.

5. DISCUSSION

Our NEB check was inconclusive. We could not rule out the possibility of a false positive. This was most likely due to the fact that our exposure time was optimized for observing TOI 5868, and thus the fluxes of nearby eclipsing binaries are too low to be helpful.

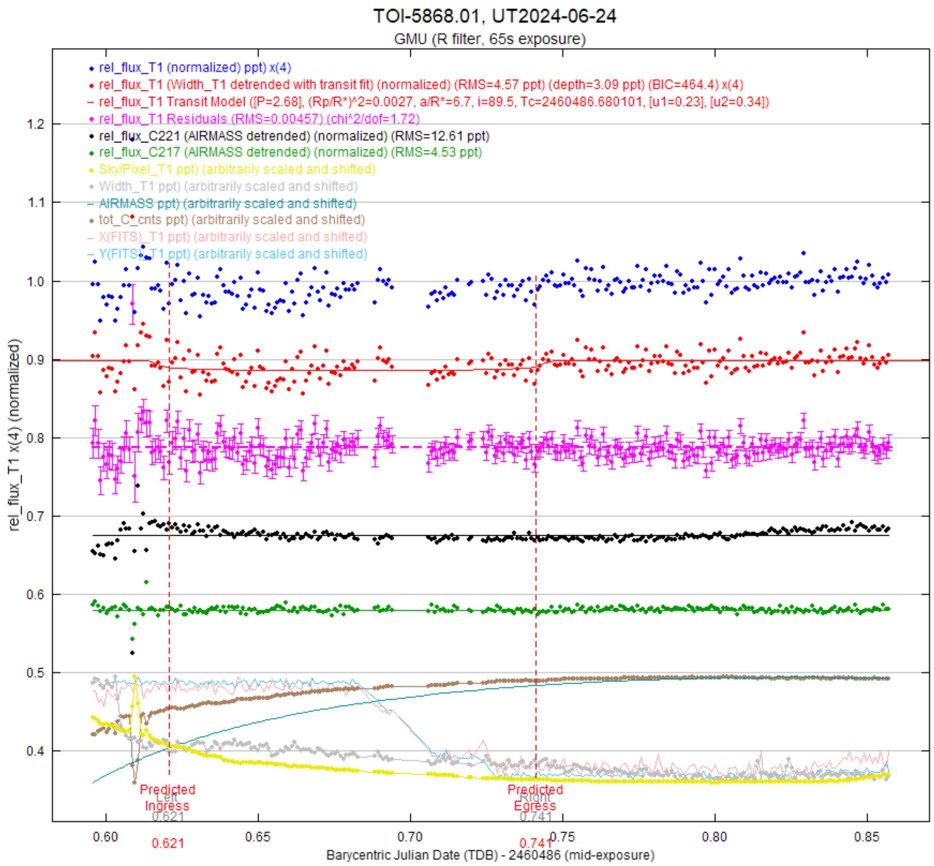

Figure 8. The final light curve from our analysis.

Our light curve shows a transit that is close to what was expected. The ingress and egress times line up almost exactly with the predicted times, shown as red dashed lines. The transit depth, 3.09 ppt, is also very close to the predicted depth of 3.3 ppt.

At around 0.615 Barycentric Julian Date, almost all of the plots showed a significant outlier. The light flux was much higher than expected for both the target and the reference stars. This is most likely because there was an error in an image that was not caught during the data preparation process.

Aside from that outlier, the plot for reference star C217 is very flat with almost no variation. However, reference star C221 shows a slight dip ranging from slightly after transit ingress to about an hour after transit egress.

Although we have some evidence for a transit, we can not conclusively say that we detected one. The RMS of the residuals is 4.57 ppt, which is larger than the transit depth we are trying to detect. We also could have gotten better results had images 107-118 not been bad due to streaking.

6. CONCLUSIONS AND FUTURE WORK

From our analysis procedure and light curve, we found that a transit of TOI 5868.01 occurred at the expected time with the expected depth. However, we could not conclusively say that TOI 5868.01 was indeed an exoplanet, as our NEB check could not rule out any stars and our error bar was too large. Future work is still necessary to confirm that TOI 5868.01 is an exoplanet.

To conclusively rule out false positives, future work opportunities include high contrast imaging to see if there are any faint nearby stars, spectroscopy to see if there are any binaries present in the spectra of TOI 5868, and statistical analysis to identify the probability of a false positive happening. After TOI 5868.01 is validated, further study can be done of its properties. Radial velocity measurements could help determine its mass and spectroscopy could be used to identify its composition. We hope that all who are interested may perform this further validation and study of TOI 5868.01.

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