Ground-based light curve follow-up validation observations of TESS object of interest TOI 5585.01

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Abstract

Starting in 2018, the NASA TESS mission identified numerous candidate exoplanets. Follow-up observations have been conducted on many of these candidate exoplanets, often involving using a light curve plot to determine whether the object of interest transits. The aims of this follow-up observation of TOI 5585.01 were to identify a transit using light curve analysis and confirm whether the details of transit, such as duration and depth, matched what was recorded by TESS. The follow-up was conducted using George Mason University's 0.8m telescope to first gather images on TOI 5585.01 during a predicted transit. Then, AstroImageJ was used to process these images, creating a final light curve and other plots and tables containing information on details of the observation data. Finally, these products were interpreted and compared to the information obtained by TESS. The results of our observation were inconclusive because a transit could not be detected due to missing data and excess noise during data collection.

1. Introduction

Billions of exoplanets, or planets orbiting stars other than the sun, likely exist outside of our solar system. Currently, over 5,600 exoplanets have been confirmed in over 4,200 planetary systems (https://science.nasa.gov/exoplanets/). The NASA TESS mission, first launched in 2018, has identified over 7,000 exoplanet candidates (https://exoplanets.nasa.gov/tess/). One method of validating that an exoplanet candidate is actually an exoplanet is to confirm that it transits, or orbits in front of and blocks the light of its host star, a necessary characteristic of an exoplanet. The details of transit are also recorded, and extensive analysis processes are used to check for false positives and negatives, determining whether another phenomenon is causing similar light patterns to a transit.

With several thousand exoplanet candidates that need to be validated, exoplanet validation is important in confirming that a candidate can be used by scientists in studies regarding exoplanets. For example, the validated exoplanets discovered during the TESS mission are used for collecting data on planet mass and diameter, allowing scientists to learn about planet composition. Due to the great number of TESS exoplanet candidates, exoplanet follow-up observations and validation are conducted with the help of numerous observatories and collaborators. The support of these observatories and collaborators allows TESS mission data to be made public more quickly, while also improving our understanding of exoplanets and the planetary systems (https://asd.gsfc.nasa.gov/archive/tess/ground_based_followup.html).

Since TESS was focused on exoplanet identification using equipment designed for viewing wide ranges, the data gathered during the mission could not be used to definitively prove or disprove whether a target of interest was truly an exoplanet. Follow-ups are needed for each and every exoplanet candidate to validate that they are truly exoplanets. Thus, many exoplanet candidates have not yet been validated and require follow-up observations.

In this paper, we present follow-up observations of TOI 5585.01. It has a radius of 8.1 R_Earth and an orbital period of 1.85 days. Its host star is class F. The goals of this follow-up observation are to determine whether the transit occurs on the expected star during the expected timeframe, and with the expected depth and duration.

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 5585.01 and our ground-based light curve analysis. In **Section 4**, we present our light curve results. **In Section 5**, we discuss the results of our light curve. **In Section 6**, we present our conclusions and future work.

2. Observations

In **Section 2.1**, we present the TESS Object of Interest 5585.01, its exoplanet candidate properties, and its host star properties using information from archival sources. In **Section 2.2**, we present the details of the TESS observation of TOI 5585.01. **In Section 2.3**, we present a summary of the observational data collected with the George Mason University 0.8m red filter telescope.

2.1 - Exoplanet Candidate and Host Star Properties

TESS Object of Interest 5585.01, also known as TIC 188389305.11, has RA and Dec (J2000) values of 129.483355 and 37.735315 degrees, respectively. The proper motions of the exoplanet candidate are -3.737 for PM RA (mas/yr) and -1.558 for PM Dec (mas/yr). It has a transit period of 1.85 days, with a transit duration of 1.44 hours and depth of 4.74 mmag, or 4.4 ppt. The equilibrium temperature of the exoplanet candidate is 1618 Kelvins (https://exofop.ipac.caltech.edu/tess/view_toi.php).

The host star of the exoplanet candidate has a stellar teff of 6457.2 Kelvins, making it a class F star. It also has a metallicity of -0.581 and a stellar log(g) of 4.44, which represents gravity.

2.2 - TESS Sector Light Curve

To generate a light curve based on data from the NASA TESS mission, we visited the Mikulski Archive for Space Telescopes (https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html) and searched for data on Object of Interest 5585.01. We then filtered the results to those taken during the TESS mission, leaving two observations remaining. The first was taken on 2020-01-21 with RA and Dec values of 09:14:48.552 and +41:03:52.70, respectively, and an exposure length of 1425.6. The second was taken on 2021-12-31 with RA and Dec values of 08:36:22.128 and +43:20:57.41, respectively, and an exposure length of 475.2. (https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html).

2.3 - GMU Telescope Observation

On 2024-02-24, we gathered data on Object of Interest 5585.01 using George Mason University's 0.8m telescope. The observations were taken using the red (R) filter. The RA and Dec (J2000) values of the target were 08:37:56.01 and +37:44:07.16, respectively. During this observation session, a total of 150 exposures with exposure times of 85 seconds each were taken between the times 22:23 and 23:50. In addition, 10 flats with exposure times of 3.5 seconds each and 20 darks, 10 with exposure times of 85 seconds each and 10 with exposure times of 3.5 seconds each, were taken.

3. Analysis

In **Section 3.1**, we present our tools used to analyze the TESS sector light curve. In **Section 3.2**, we present our analysis of the ground-based light curve using AstroImageJ.

3.1 - Analysis of TESS Sector Light Curve

Even though we located the TESS mission data on TOI 5585.01 on the Mikulski Archive for Space Telescopes, we were unable to download any data files. As a result, we could not generate or perform an analysis of the TESS sector light curve.

3.2 - Analysis of Ground-based Light Curve Using AstroImageJ

The primary tool used for this analysis was AstroImageJ. The package was downloaded via http://www.astro.louisville.edu/software/astroimagej/installation_packages/AstroImageJ_v5.3.3.00-windows-x86_64Bit.exe. The tools and windows referenced in the following paragraphs, unless stated otherwise, are part of the AstroImageJ software.

First, we opened and viewed the FITS files containing the images recorded by George Mason University's 0.8m telescope during the 150 exposures. We examined the images for any bad images that contained streaking, unwanted light from external sources, and other undesirable properties, ultimately removing 6 defective images. Then, to prepare for data processing, we entered the observatory information and the target's properties, as mentioned in **Section 2.1**, into the DP Coordinate Converter. We also checked that the dynamical time of the program was set to automatically update, updating the timestamps of the images in BJD. With this complete, we used the CCD Data Processor to produce two master darks, one per exposure time, and a master flat, created with the 3.5 second master dark, based on the darks and flats we had previously obtained. Using the 85 second exposure time master dark, the master flat, and the coordinate converter, we data-reduced the images. To plate-solve the images, we downloaded the Astrometry.net Local Solver ansvr plugin (https://adgsoftware.com/ansvr/) and connected it to the same port as AstroImageJ, allowing us to plate-solve the images through AstroImageJ.

With the images now data-reduced and plate-solved, we worked on creating a measurement table for the light curve using the Aperture Photometry Tool. First, we identified the location of the TOI on a plate-solved image with the help of a finder chart (generated using https://astro.swarthmore.edu/transits/finding_charts.cgi) and selected it as the target. **Figure 1** presents the seeing profile plot of TOI 5585.01 created using the Seeing Profile astronomy plugin on AstroImageJ and the selected target on the plate-solved image.

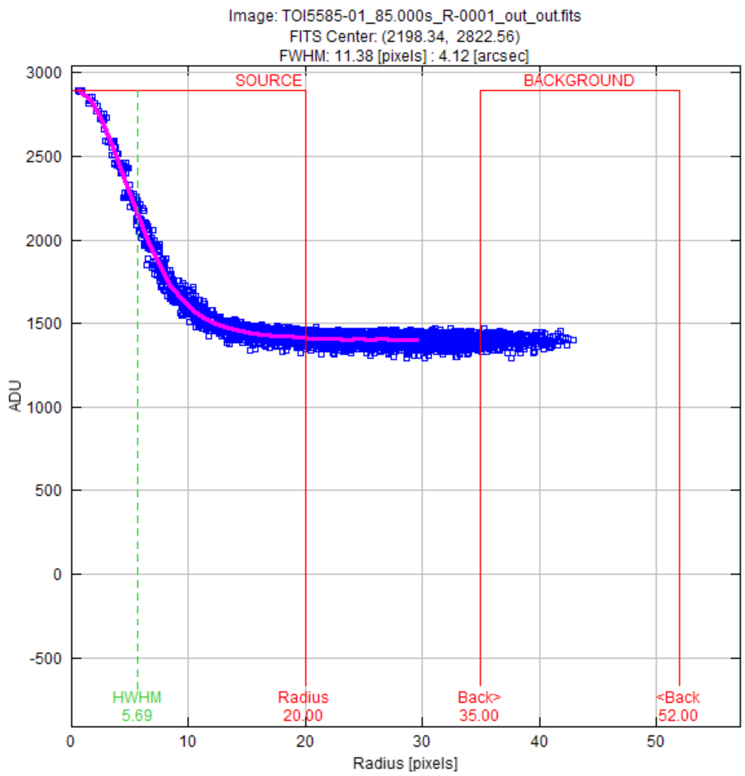

Figure 1. Seeing profile plot of TOI 5585.01. *Note. This image displays the values that determine the distance ranges containing neighboring stars and reference stars. The important values to note are the source radius and the background "Back" values.*

Figure 1 displays that the aperture radius value is 20 and the inner and outer radii of the background annulus are 35 and 52, respectively. Entering these values, along with the GMU telescope camera's CCD specifications, into the Aperture Photometry Settings completes the preparations for multi-aperture photometry.

To conduct multi-aperture photometry, we began by placing a 2.5' circle around the target, with a search radius of 150 and circle radius of 416.667, which is based on the specifications of the GMU telescope's CCD. In addition, we added the data from a Gaia stars .radec file generated from the date of observation. **Figure 2** presents the resulting aperture placements within the circle created by the Gaia stars .radec file. Next, we opened the "Multi-Aperture Measurements" window, calibrated the settings to match the specifications of the image and target, and began to place additional apertures. Apertures represent reference stars that would be used for light comparison with the target later in the analysis, ideally having around 8-10 for a thorough analysis. AstroImageJ provided several candidates for reference stars, which required confirmation on whether they would serve as good reference stars. Stars that moved away from the field of view of the images or did not constantly produce enough light to remain visible had their apertures removed. **Figure 3** presents the resulting aperture selections.

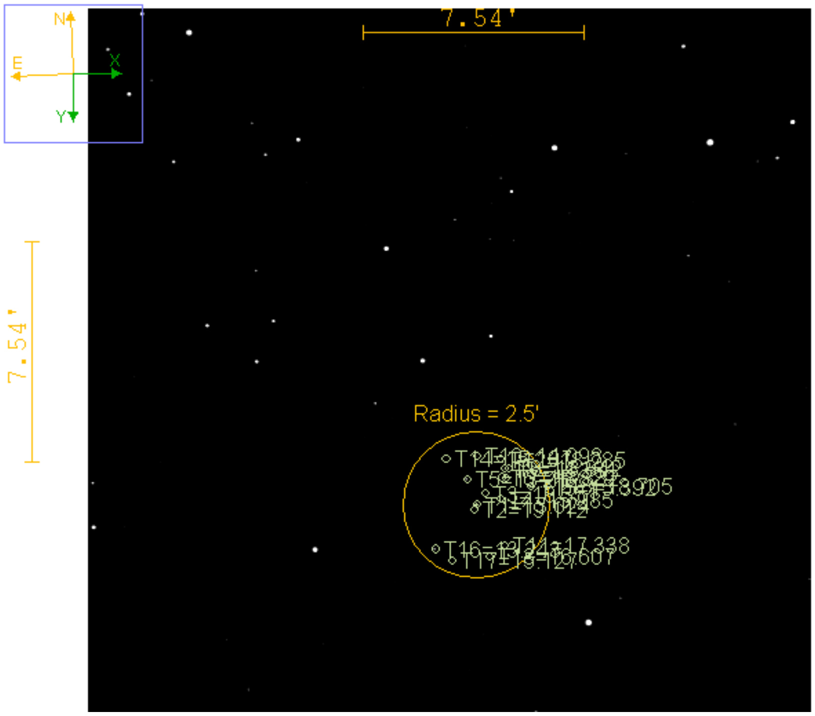

Figure 2. Field image of TOI 5585.01 with Gaia stars. *Note. This image displays the apertures of neighboring stars placed by the Gaia stars .radec file.*

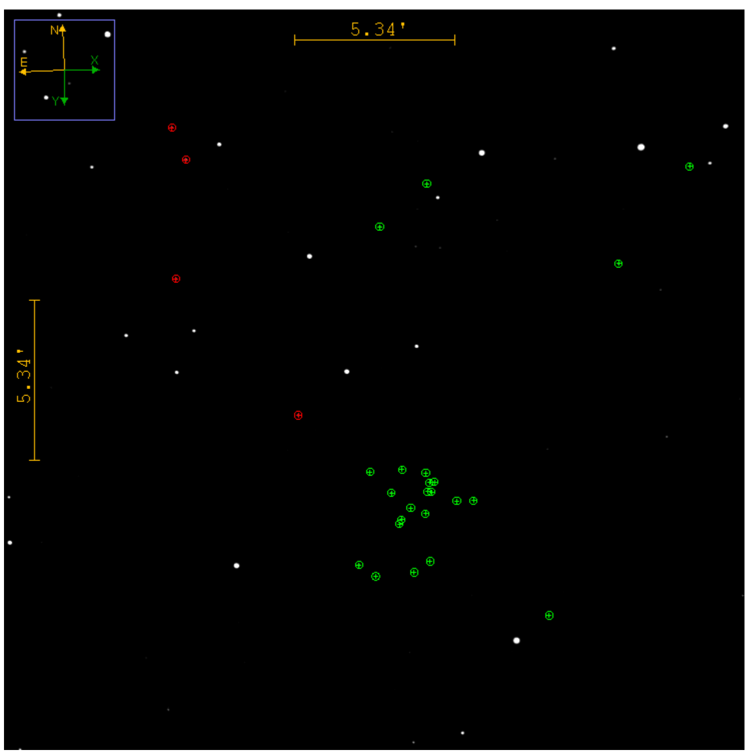

Figure 3. Field image of TOI 5585.01 containing aperture placements. *Note. This image displays the aperture placements of both neighboring stars and reference stars. The red apertures represent the reference stars, while the green apertures represent the neighboring stars and removed reference star apertures.*

With the apertures placed, we saved the aperture selections and completed the processing of the reference stars, creating a measurements table that we saved. With the apertures and measurements table, we were able to begin light curve generation. In order to comply with TESS/K2 reporting guidelines, we began by opening a plot configuration based on a template provided by http://www.astrodennis.com/Template.zip.

In the “Multi-plot Main” window, we entered the target’s predicted ingress and egress times of 0.6466 and 0.7066, respectively, representing the start and end times between which the transit is predicted to occur, along with adjusting basic plot settings. Next, in the “Data Set 2 Fit Settings” window, we entered the information on the object of interest and its host star mentioned in **Section 2.1**. For now, we enabled the plot to show residuals and error while disabling all detrending parameters, creating a preliminary light curve plot.

Afterwards, we began calibrating the data. In the “Multi-plot Y-data” window, we enabled plotting of the parameters Sky/Pixel_T1, Width_T1, AIRMASS, tot_C-cnts, X(FITS)_T1, and Y(FITS)_T1. Furthermore, we adjusted the scale, shift, and color of these parameters in accordance with the TFOP SG1 Guidelines (http://www.astrodennis.com/TFOP_SG1_Guidelines_Latest.pdf). Next, we reviewed each of the reference star’s flux, unselecting them on the “Multi-plot Reference Star Settings” window if their data points showed great variation or significantly increased the RMS value of the plot. These new apertures and the updated measurements table created using these new apertures were saved.

Lastly, before creating the finalized light curve plot, we performed a NEB check of the neighboring stars noted by the Gaia stars .radec file. Setting the “TFOP SG1 NEB Analysis Macro” window to generate a table for stars cleared as potential NEBs, plots for every star’s flux data, and a Delta magnitude vs. RMS plot, we entered the target’s predicted ingress and egress values and provided the measurements table and a plate-solved image, generating the desired files. **Figure 4** displays a plot for a reference star’s flux data. **Figure 5** displays the dmagRMS-plot generated.

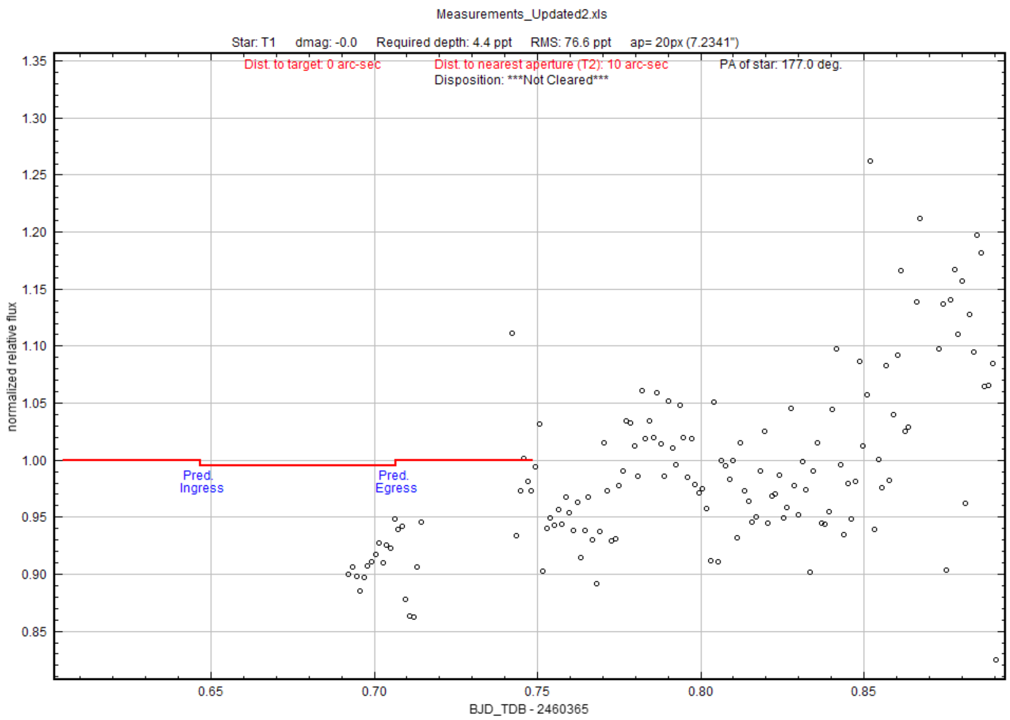

Figure 4. Flux plot for T1. *Note. This plot displays the flux of the light of a reference star in terms of Barycentric Julian Date (TDB).*

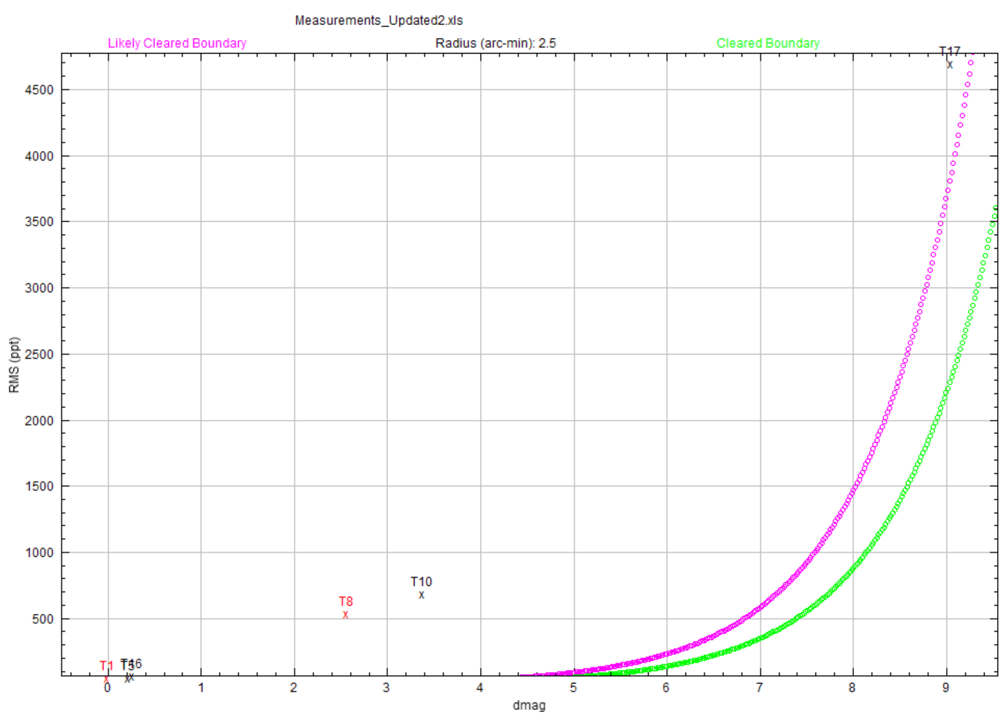

Figure 5. dmagRMS-plot for neighboring stars of TOI 5585. *Note. This plot compares the delta magnitude of comparison stars within 2.5 arcmin of the TOI to that of the TOI, displaying scatter. Any reference star placed below the green line on the plot is cleared as a nearby eclipsing binary.*

There are no significant outliers on **Figure 4**, though only certain neighboring stars are shown on the plot. Thus, we further refined the aperture selection to only include the neighboring stars shown on the plot among all the available neighboring stars. These new aperture selections and the updated measurements table created using these apertures were saved as the final apertures and measurements for the light curve.

With the processing of the Y data finished, we adjusted the shown reference star data points, shift, scale, and detrending parameters with the aim of reducing the RMS value and producing a readable plot. Upon completing this step, we had generated a complete light curve plot for TOI 5585.01.

4. Results

In **Section 4.1**, we present our final ground-based light curve plot for TOI 5585.01 created using AstroImageJ.

4.1 - Ground-based light curve plot

Figure 6 presents our final ground-based light curve plot for TOI 5585.01.

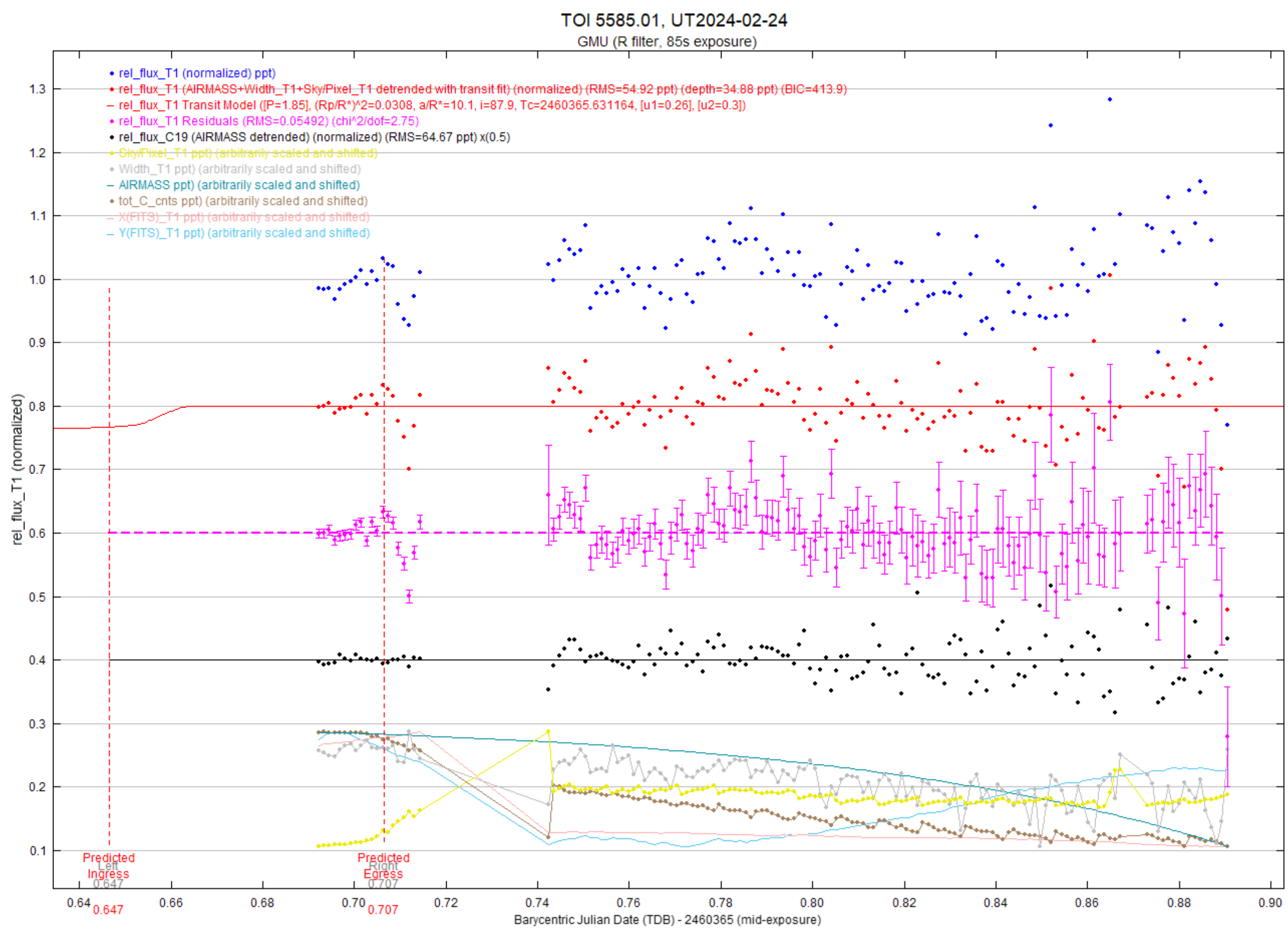

Figure 6. Ground-based light curve plot for TOI 5585.01. *Note. This plot is the cumulation of the data gathered throughout the observation and represents the final product of this follow-up. It displays various light fluxes in terms of Barycentric Julian Date (TDB), values indicating the details of transit, and statistical values regarding the certainty and error of data.*

The blue data points aligned on 1.0 of the y-axis represent light from the target. The red and pink data points below it represent the detrended version of the light from the target and its residuals. The detrended data shows an RMS of value of 54.92 and a transit depth of 34.88 ppt. The residuals show that there is an RMS value of 0.05492 and a chi^2/dof value of 2.75. The black data points represent the light from a chosen reference star, detrended using AIRMASS. Lastly, the yellow, brown, gray, light blue, teal, and pink lines near the bottom of the plot represent the detrending parameters. The predicted ingress and egress can also be seen as the red dashed lines placed vertically on the left side of the plot.

5. 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.

5.1 - Interpretation of Our Results

Overall, this observation was inconclusive in determining whether the target of interest was a transiting exoplanet. Most of the data was taken outside of the predicted ingress and egress, likely due to clouds and poor weather during observation, leading to the inability to confirm whether a transit occurred in the predicted time frame. Furthermore, the data was too noisy to detect a transit. Having a chi^2/dof value of 2.75, while not terrible, leaves great room for improvement. In terms of the amount of noise, the residual RMS value is greater than 0.05, which is the threshold for an acceptable amount of noise. The detrended data's RMS value of 54.92 ppt also could easily cover the transit, no matter if the true transit depth is 34.88 ppt or the expected 4.4 ppt. The high flux illustrated by **Figure 4** and the other NEB-check plots suggest that the light from certain reference stars could be the source of some of this noise. However, since none of the stars shown in **Figure 5** are below the green curve, there are no cleared NEBs. Ultimately, the data from this observation cannot be used to confirm a transit due to the excess of noise during data collection. This observation does contain a transit depth that differs greatly from what was expected from TESS, but since the observation data is noisy and likely contains inaccuracies, there is not a definite contradiction in transit depths.

5.2 - Results in the Context of Candidate Exoplanet Follow-ups

This candidate exoplanet would be considered a "hot" hot Jupiter since its equilibrium temperature is 1618 Kelvins (2452.73 degrees Fahrenheit), which is between the range of 1,300 and 3,100 degrees Fahrenheit (https://science.nasa.gov/universe/exoplanets/cosmic-legacy-retired-space-telescope-reveals-hot-jupiter-secrets/). That means that the exoplanet candidate is likely a gas giant that orbits its host star very closely, as demonstrated by its period of 1.85 days. We know the existence of other hot Jupiters with similar temperatures. For example, TOI 778 has an equilibrium temperature of 1450 Kelvins (2150 Fahrenheit) and an orbital period of 4.6 days, making it another "hot" hot Jupiter (https://exofop.ipac.caltech.edu/tess/view_toi.php).

6. Conclusions and Future Work

Our observation of TOI 5585.01 does not definitively confirm that the object of interest is a transiting exoplanet. The lack of data between the predicted ingress and egress and excess of noise lead to the data being inconclusive.

In terms of future work, more observations and follow-ups of TOI 5585.01 should be conducted to further validate if it is a transiting exoplanet. Effort should be spent trying to limit the amount of noise during data collection in order to gain a more accurate set of data. In addition, a false-positive validation analysis should be conducted to determine whether the "transit" was the result of another phenomena, such as a nearby eclipsing binary.

References:

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