Ground-based light curve follow-up validation observations of TESS Object of Interest (TOI) 5907.01

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Abstract

The TESS mission, standing for the Transiting Exoplanet Survey Satellite, is a NASA guided mission that looks for potential exoplanets using the transit method. When the satellite sees a potential exoplanet, it does not immediately validate the presence of an exoplanet, instead turning it into one of TESS Objects of Interests (TOIs) and letting researchers conduct ground-based follow-up validations to confirm. Our research was conducted on TESS Object of Interest 5907.01. The goal was to investigate and confirm if a transit had occurred. Additionally, we wanted to confirm if our results matched the expected duration, depth, and transit start and end times predicted by TESS. Our initial results show that a very faint transit occurred. Additional work suggests that TOI 5907.01 likely is an exoplanet.

1. Introduction

Over 5,000 exoplanets that have so far been discovered were discovered by the transit method [3]. NASA and scientists around the world have been observing space all around Earth with the TESS program since 2018 when it was first launched to look for various exoplanets orbiting stars in the Milky Way Galaxy [4]. As this NASA satellite scans the sky, when it finds something that may resemble an exoplanet, it marks it as a candidate exoplanet and assigns to it a TESS Object of Interest (TOI) number. This allows observers on Earth to continue research on this specific Object of Interest with ground-based telescopes to confirm the presence of an exoplanet. Exoplanets are found primarily by the transit method. A transit occurs when a planet orbits in front of its star. When this happens, the amount of light observed from the star decreases. After the planet passes over, the amount of light observed returns to its previous value. By studying this pattern of light on a specific TESS Object of Interest, an observer can then graph this data in light curves and look for a drop in light as a way to validate the existence of an exoplanet [1].

TESS has and continues to discover exoplanet candidates. Numerous ground-based observations, using various telescopes around the world to confirm the features of the TESS exoplanet candidates, have been performed with varying results accompanied by numerous papers written. Our team is one of the several conducting this kind of observation to help NASA and the TESS Mission collect data.

This particular research, presented in this paper, focuses on a candidate that has never been observed in depth by any ground-based telescope. The data gathered here will directly help NASA in their future missions, some of which include the continued search for extraterrestrial life and discovering what these exoplanets are made of. This observation will assist NASA in the overall hunt for exoplanets.

This paper investigates TESS Object of Interest 5907.01 with the goal of finding a transit. Furthermore, we seek to confirm if the duration of the transit matched what was predicted by TESS, if the transit happened at the predicted time, and if the transit occurred with the predicted depth. If any of these characteristics are off or incorrect, we take note of it. So far, it is known that TOI 5907.01 has a predicted transit duration of 0.796 hours or 47.76 minutes, at transit time of 23:54 PM to 00:42 AM EDT, occurring on the night of June 28th, 2024. Additionally, the period is predicted to be 0.66 days, with the depth and radius of 3.7 ppt and 8.3 Earth radii (0.74177 Jupiter radii) respectively.

This paper covers the entire research process, starting with the observations and analysis of TOI 5907.01. In Section 2, we present our observations from TESS and the George Mason University's 0.8m telescope. In Section 3, we present our analysis of the TESS light curve for TOI 5907.01 and our ground-based light curve analysis. In Section 4, we present our light curve results. In Section 5 we discuss our results, and finally, in Section 6 we present our conclusion and recommendation for future work.

2. Observations

In Section 2.1, we present a summary of the observational data collected by the George Mason University 0.8m telescope on TESS Object of Interest 5907.01. In Section 2.2 we present the properties of the exoplanet candidate and those of its host star.

Section 2.1 - Collected Data

The data for TOI 5907.01 was collected on the night of June 28th, 2024 at the observatory at George Mason University using their 0.8m telescope. The filter used was an R filter. Approximately, a total of 172 images were taken, each with a 90-second exposure time. Data collection started at approximately 21:50 PM EDT on the 28th and ended at approximately 4:35 AM on the 29th, local time. The RA and Dec, its celestial coordinates, are 21:00:52.78 and +17:06:59.14 respectively.

Section 2.2 - TESS Data

TESS provides several characteristics associated with this candidate exoplanet and its host star, along with their approximated or predicted values.

Candidate exoplanet:
Orbital period = 0.66 days
Transit depth = 3.74 ppt.
Transit duration = 0.796 hours
Radius = 8.3145 Earth radii or 0.74177 Jupiter radii

Transit start time = 0490.6668 BJD
Transit end time = 10490.7002 BJD

Host star:
Effective temperature = 5,766.00 K
Stellar radius = 1.080 solar radii
Stellar surface gravity (log10(cm/s^2)) = 4.384 cm/s^2
Stellar luminosity = 0.06518 Watt
Stellar density = 1.152 g/cm^3
Stellar mass = 1.030 Solar Mass

The TESS Input Catalog (TIC) for TOI 5907.01 is 387318486.01.

3. Analysis

In Section 3.1, we present our tools used to analyze TOI 5907.01 which include AstroImageJ and ExoFAST. In Section 3.2, we present the method of processing the data and generating a light curve using AstroImageJ.

Section 3.1 - Tools

AstroImageJ Tool
AstroImageJ is the tool used to process and interpret the images and data collected. This program makes possible visualization of the images taken and allows users to conduct data-reduction, plate-solving, multi-aperture photometry, light curve generation, and NEB checks.

ExoFAST Tool
ExoFAST is the tool that helps to determine the properties of the candidate exoplanet after a measurement table from AstroImageJ and known data from TESS are imputed in. This tool generates information and graphs that can be used to determine what kind of exoplanet was found.

Section 3.2 - Methods

There are many steps taken in AstroImageJ to generate light curves of TOI 5907.01.

We first organized all the images taken from the GMU telescope. There are three types of images: darks, flats, and science images. These image types are organized into groups. AstroImageJ is used to view these images. Each science image is inspected to rid the group of bad images, namely images with streaking stars, targets outside the field-of-view, or targets that move around too much among other images. Of the 172 images collected that night, only 79 science images were usable.

Next is the data-reduction. Data-reduction is the step in which the dark, flat, and science images are used together to clean up the images. These images are oftentimes very messy and full of detector effects that are not wanted. This step rids the images of undesirable effects, resulting in clearer and smoother science images that are more ideal for light curve generation.

The data-reduced images are then plate-solved. Plate-solving involves aligning each image around specific celestial coordinates in order to keep the stars at the same place on every image. By using AstroImageJ paired with astrometry.net, we can center each image around the RA and Dec coordinates. This helps in generating an ideal light curve.

A light curve will now be generated using the plate-solved data from the previous step.

First, we find our target and determine the aperture size. By opening a Seeing Profile, we determine the radius as well as the annulus sizes. This can be seen in Figure 3.1.

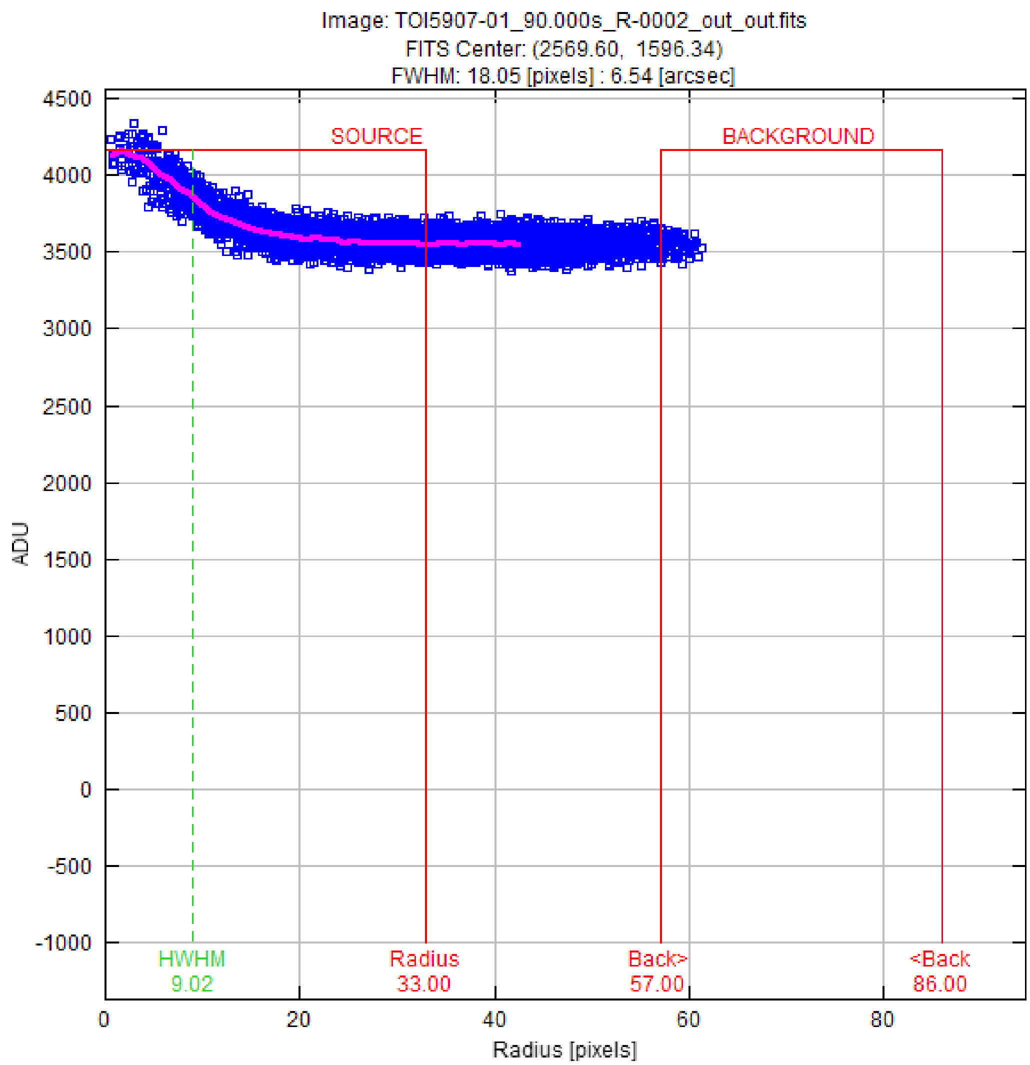

Figure 3.1 - TOI 5907.01 Seeing Profile

With this data, we can now perform multi-aperture photometry. We input a value of 33.00 for its radius, 57.00 for its inner annulus size, and 85.00 for its outer annulus size into AstroImageJ. Then we import a gaia stars .radec file to automatically locate known stars taken from the Gaia database. Finally, we select multiple stars with roughly the same size and brightness as our target star for references as seen in Figure 3.2. There are 14 reference stars and 87 gaia stars. After multi-aperture photometry is complete, we generate a measurement table which can be used to generate a light curve.

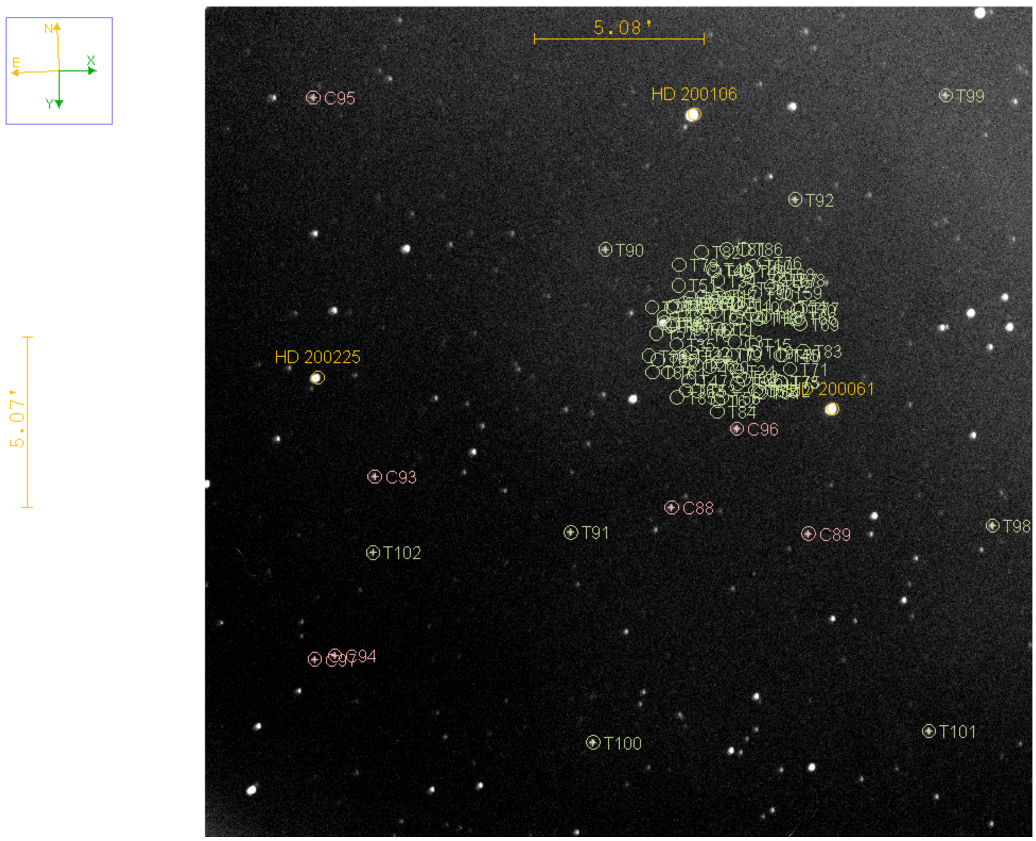

Figure 3.2 - Field of View Aperture

We can now plot the light curve of TOI 5907.01. We start by uploading a default template which changes the settings of AstroImageJ to the proper settings which are necessary for our research. Next, we input the predicted transit start and end times in BJD as well as the target's orbital period. These values are 0.6668, 0.7002, and 0.66 days, respectively. We then enter the host star's stellar radius. This value is 1.080. We also enter the Linear LD u1 and Quad LD u2 values which are 0.36631017 and 0.2803521, respectively. Once all the values are entered correctly, we generate the light curve for TOI 5907.01. Included in the graph is a reference star flux plot. We check each reference star for scattering and remove the ones with large scatter. We then perform a NEB check to filter for false positives which generates another graph. We check for any possible nearby eclipsing binaries and check their individual plots for a potential transit that may indicate a false positive. Lastly, we input known TESS values as well as our measurement table into ExoFAST to generate the exoplanet properties as well as another light curve

4. Results

In Section 4.1, we present the TOI 5907.01 light curve generated from AstroImageJ as well as a light curve from ExoFAST. In Section 4.2, we present the exoplanet's properties from ExoFAST.

Section 4.1 - TOI 5907.01 Light Curves

Figure 4.1 depicts the TOI 5907.01 light curve generated from AstroImageJ. This graph contains 11 total plots: four target star flux plots, one reference star flux plot, and six detrending parameter graphs. The first, blue plot is the raw, normalized flux with no effects on it. The red plot under it is a detrended graph with Width_T1 which adjusts the plot to take into account how light is spread out on the telescope detector. The third pink plot is the residuals, which is the error associated with the red plot. The fourth green plot is detrended with X(FITS)_T1 which is the shift of the target on the x-axis. The fifth plot is a reference star plot from reference star C88. The remaining six graphs are detrending parameters which help correct our data.

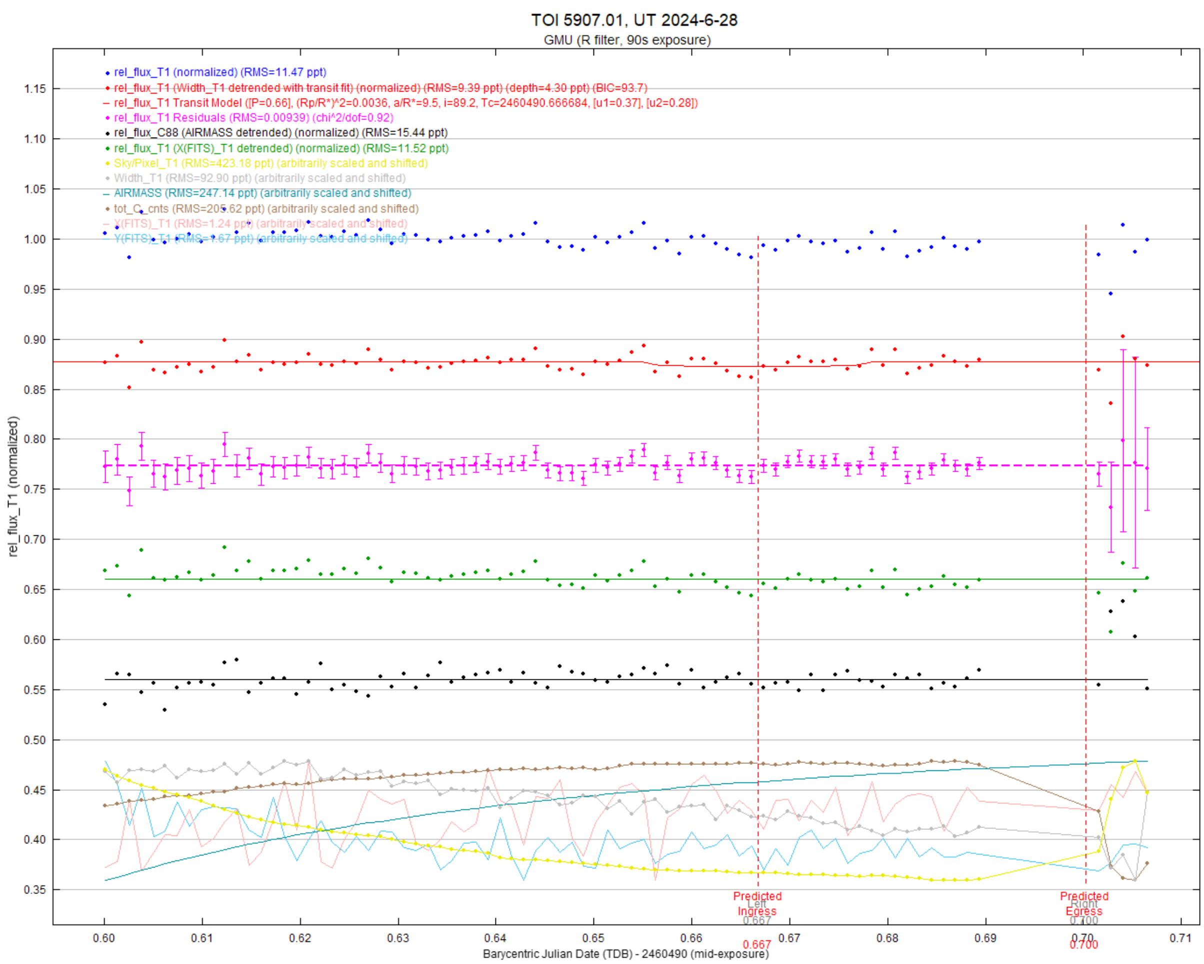

Figure 4.1 - TOI 5907.01 Light Curve

Figure 4.2 is a plot of the normalized flux plot versus time generated from data input in ExoFAST which also includes error.

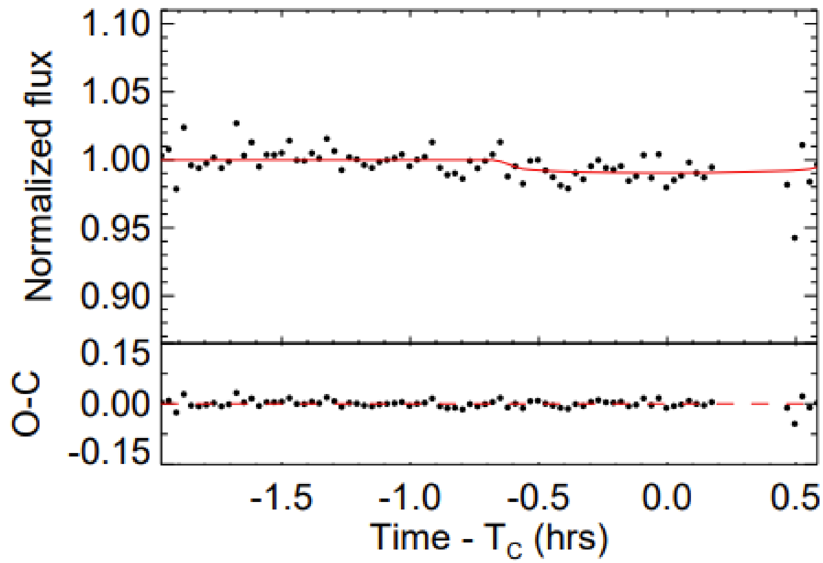

Figure 4.2 - Normalized Flux Plot

Section 4.2 - ExoFAST Data

Transit fit:
Chi^2/dof = 1.1103047
Scaling errors by 1.0588286
RMS of residuals = 0.010248468

Combined fit:
Chi^2 of Transit data = 68.327634 (79 data points)
Chi^2 of Priors = 0.00061359775 (2 priors)
Chi^2/dof = 1.0353852

Planetary Parameters:

e	Eccentricity	0.015634
omega_*	Argument of periastron (degrees)	-178.625165
P	Period (days)	0.658317
a	Semi-major axis (AU)	0.014981
R_{P}	Radius (rj)	0.691171
T_{eq}	Equilibrium Temperature (K)	2020.903518
fave	Incident flux (fluxcgs)	3.782247

Primary Transit Parameters:

T_C	Time of transit (bjdtdb)	2460490.682168
R_{P}/R_{*}	Radius of planet in stellar radii	0.089837
a/R_{*}	Semi-major axis in stellar radii	4.074460
u_1	linear limb-darkening coeff	0.371271
u_2	quadratic limb-darkening coeff	0.275666
i	Inclination (degrees)	89.991726
delta	Transit depth	0.008071
T_{FWHM}	FWHM duration depth(days)	0.051988
tau	Ingress/egress duration (days)	0.004768
T_{14}	Total duration (days)	0.056755

5. Discussion

In Section 5.1, we present our interpretation of our light curve of TOI 5907.01 as well as the ExoFAST data found previously. In Section 5.2, we analyze the dmagRMS plot and check for any nearby eclipsing binaries that could indicate a false positive.

Section 5.1 - Data Interpretation

Based on the results found, it is likely that an exoplanet does exist in TOI 5907.01. However, the data collected suggests a higher than ideal amount of uncertainty associated with our findings.

From the light curve graph in Figure 4.1, we can see a very slight dip right before the ingress which continues through the predicted transit time. Refer to Figure 5.1 for a zoomed in image. We can see that the line of best fit indicates a dip in the data which strongly suggests a transit occurrence. The graph displays a depth of 4.30 ppt, which is close to the expected depth of 3.7 ppt from TESS. But because the depth found was larger than the expected depth, there is now more uncertainty and error due to the higher scatter. Notice that Figure 4.2, the normalized flux plot has a slight dip, but no rise. This is probably due to the lack of images on the egress side due to inclement weather.

Data collected from ExoFAST further gives us valuable information about this exoplanet. The period was found to be 0.658317 days, which hits our goal of 0.66 days. The radius was found to be 0.691171 Jupiter radii, which is close to the target of 0.74177. The transit duration was found to be 0.004768 days, or 0.114432 hours, which is significantly shorter than the TESS duration of

0.796 hours. Finally, the exoplanet has a temperature of 2,020.903518 Kelvin, or 3,177.956332 Fahrenheit.

These numbers combined point to the presence of an ultra-hot Jupiter. An ultra-hot Jupiter typically has a temperature of 3,100 Fahrenheit or higher [2]. Our exoplanet has a temperature of around 3,177 Fahrenheit, which is right within the temperature range. The orbital period is also very short, which is another characteristic of an ultra-hot Jupiter [2]. However, the radius of this exoplanet is only 0.691171 Jupiter radii, which is smaller than the size of Jupiter.

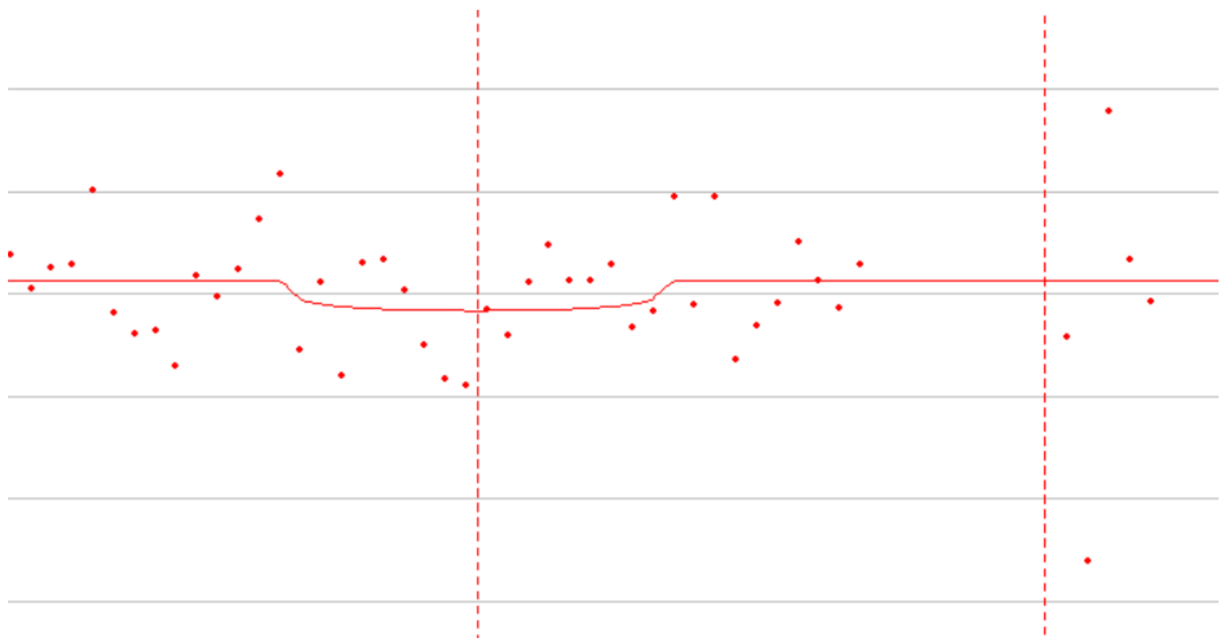

Figure 5.1 - Zoomed in TOI 5907.01 Light Curve

Section 5.2 - dmagRMS Plot & False Positives

Finally, we have to check for nearby eclipsing binaries that may suggest a false positive. Figure 5.2 portrays an NEB (Nearby Eclipsing Binary) check graph where any reference star under the green line would indicate a cleared star and any reference stars over it would not be cleared. Unfortunately, all of our reference stars cannot be cleared as non nearby eclipsing binaries. Any of these stars could be eclipsing binaries, the fact of which necessitates more examination in the future. As of now, the results from this check are inconclusive.

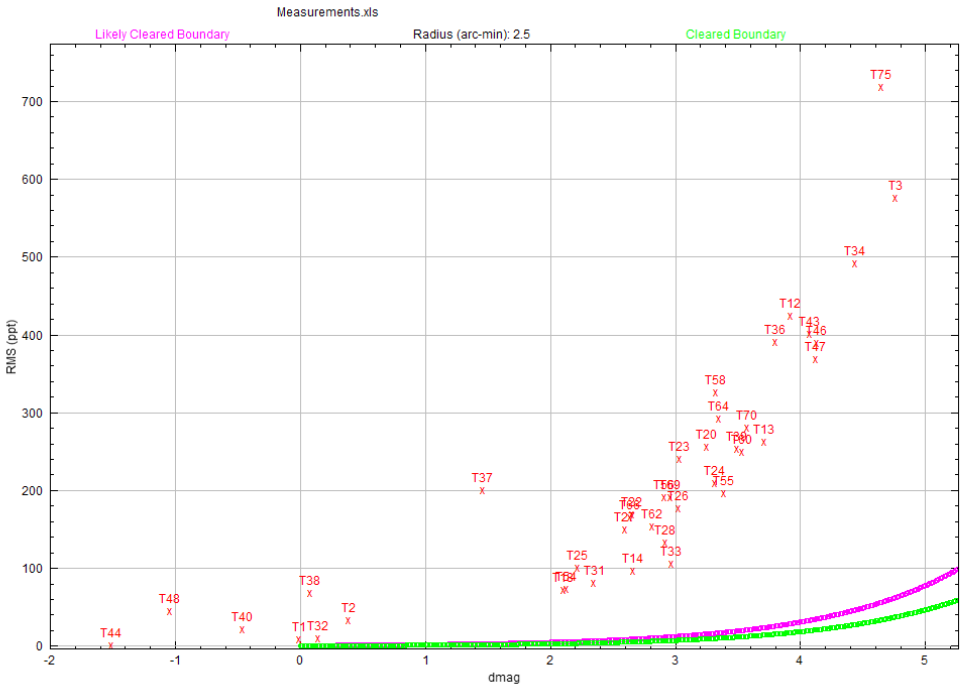

Figure 5.2- dmagRMS Plot

6. Conclusion and Future Work

Based on the interpretation of the data collected as well as the AstroImageJ and ExoFAST light curves, we conclude that TOI 5907.01 is likely an exoplanet. We were able to confirm that the depth, mass, period, and radius were close to the predicted values found by TESS. This exoplanet fits the characteristics of an ulta-hot Jupier. It has a temperature of around 3,177 K, which is the temperature range typical of these ultra-hot Jupiters. It also has a very short orbital period which is common for these types of high temperature Jupiter-sized exoplanets. However, we note that this conclusion has some uncertainties, for example, the transit observed on the light curve occurs before the ingress and concludes before reaching the egress, and the transit duration is significantly shorter than what TESS found. However, if we shift the ingress and egress lines to line up with the observed transit, we can see that the transit duration is within the same magnitude of what has been observed by TESS. Furthermore, if the missing data due to inclement weather were available, the curve-fit transit duration may have been lengthened and thus may better match the TESS observation data.

We believe that TOI 5907.01 can benefit from further research, specifically to obtain more data to generate a light curve with a more conclusive and visible transit. Future research is also needed to filter out false positives as the result in the NEB check (Figure 5.2) shows inconclusive data. Finally, conducting additional data collection with ExoFAST to match characteristics from TESS will give a clear conclusion on the type of exoplanet found. These additional steps will help to conclusively validate the existence of this exoplanet.

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