Ground-based light curve follow-up validation observations of TESS object of interest TOI 5907.01

Norah C. McCuin[1] and Peter Plavchan[2]
[1]Hayfield Secondary School, Alexandria, VA., USA
[2]Department of Physics and Astronomy, 4400 University Drive MS 3F3, George Mason University, Fairfax, VA 22030, USA

Abstract

The goal of this study was to validate the potential exoplanet TOI 5907.01. While TOI 5907.01 was identified by the Transiting Exoplanet Survey Satellite (TESS), it has yet to be confirmed as an exoplanet through ground-based follow-up observations. Using images of TOI 5907.01 taken at the George Mason University observatory in combination with transit data from the NASA exoplanet archive, we produced a light curve plot in AstroImageJ (AIJ) to visualize the transit of TOI 5907.01 as it moved in front of its host star. Upon further analysis, our data was shown to match well to the data collected by TESS, however, we could not confirm TOI 5907.01 as an exoplanet due to the possibility that a nearby eclipsing binary star was the cause of the transit event we observed.

Section 1: Introduction

The first exoplanet was discovered in 1992, and since then, the means of exoplanet discovery have greatly expanded (https://www.cfa.harvard.edu/research/topic/exoplanets). In less than 35 years, other unique methods of exoplanet detection have been created, while many telescopes, satellites, and observatories have been utilized for exoplanet observation (https://www.cfa.harvard.edu/research/topic/exoplanets). For example, the Transiting Exoplanet Survey Satellite (TESS).

TESS was launched on April 18th, 2018, and concluded its primary mission on July 4th, 2020. In that time, TESS identified 7,203 exoplanet candidates, of which only 542 have been confirmed (https://exoplanets.nasa.gov/tess/). TESS identifies exoplanet candidates by taking two minute exposures of the 200,000 brightest stars in the sky, in addition to 30 minute exposures of every visible star in the sky (https://www.cfa.harvard.edu/facilities-technology/telescopes-instruments/transiting-exoplanet-survey-satellite- tess). Exoplanet candidates can then be seen when they pass in front of their host star, since their transit causes a noticeable dip in the brightness of the star.

After exoplanet candidates are identified through this process, they need to be validated by ground-based follow up observations conducted by independent observatories. While most exoplanets have been confirmed using the transit method (https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html), thousands of planet candidates from the TESS mission are still unconfirmed. Similar papers that use the transit method have yielded a range of results: a study conducted in 2022 was able to confirm an exoplanet and characterize it using the transit method coupled with data from the TESS mission (Addison et al. 750). On the other hand, another study published in the Journal of Astro-Scholars Research in 2023 was inconclusive due to the limitations of the transit method (Joseph and Plavchan 139).

TESS Object of Interest (TOI) 5907.01 is one of the thousands of unconfirmed exoplanet candidates identified by the TESS mission. The goal of this paper is to investigate the validity of TOI 5907.01, since there are currently no papers regarding this topic.

In this paper, we present follow-up observations of TOI 5907.01. According to the NASA Exoplanet Archive, TOI 5907.01 has a planetary radius of ~8.31454 R_Earth and an orbital period of ~0.6583175 days. TOI 5907.01 orbits a star with a stellar effective temperature of ~5766 K, similar to that of the Sun. Our goal in this paper is to investigate whether or not the transit of TOI 5907.01 occurs at the expected time, with the expected duration and depth as determined by TESS.

In Section 2, we present our Observations from TESS and the George Mason University 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 in Section 6, we present our conclusions and future work.

Section 2: Observations

In Section 2.1 we present the TESS Object of Interest 5907.01 and its exoplanet candidate properties, its host star properties from the TESS Input Catalog, the Gaia mission, and other archival sources. In Section 2.2 we present the TESS sector light curve(s). In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1

According to the NASA Exoplanet Archive, TOI 5907.01 has a planetary radius of ~8.31454 R_Earth and an orbital period of ~0.6583175 days. Its transit duration was ~0.796 hours, roughly 48 minutes, and its transit depth was 3.7 ppt. TOI 5907.01 is also believed to have a planet equilibrium temperature of 1963 K.

TOI 5907.01 orbits a star with a stellar effective temperature of ~5766 K and a stellar radius of ~1.08 R_Sun, making it very similar to our own Sun. TOI 5909.01's host star is ~456.741 pc away from TOI 5907.01.

Other than the NASA Exoplanet Archive, we also utilized other archival sources for our analysis of TOI 5907.01. The Mikulski Archive for Space Telescopes (MAST) was used to obtain a TESS light curve of TOI 5907.01 to serve as a reference to our own.

We also used data from the Gaia Mission to search for nearby eclipsing binaries (NEBs) that could be the source of a false-positive transit event detected by TESS. The Gaia space observatory was launched in December of 2013. Its objective was to create the largest three-dimensional view of the Milky Way to date, and has since observed over a billion stars (www.esa.int/Science_Exploration/Space_Science/Gaia_overview). We downloaded an aperture file from the Gaia mission that contained all the stars in the Gaia database near TOI 5907.01 that needed to be checked as possible NEBs.

2.2

In this section, we present the TESS light curve of 5907.01 generated by MAST using LCviz. The tools used to generate this light curve are elaborated on in section 3.1. This light curve plot displays the observation of 5907.01 by TESS on August 5th, 2022.

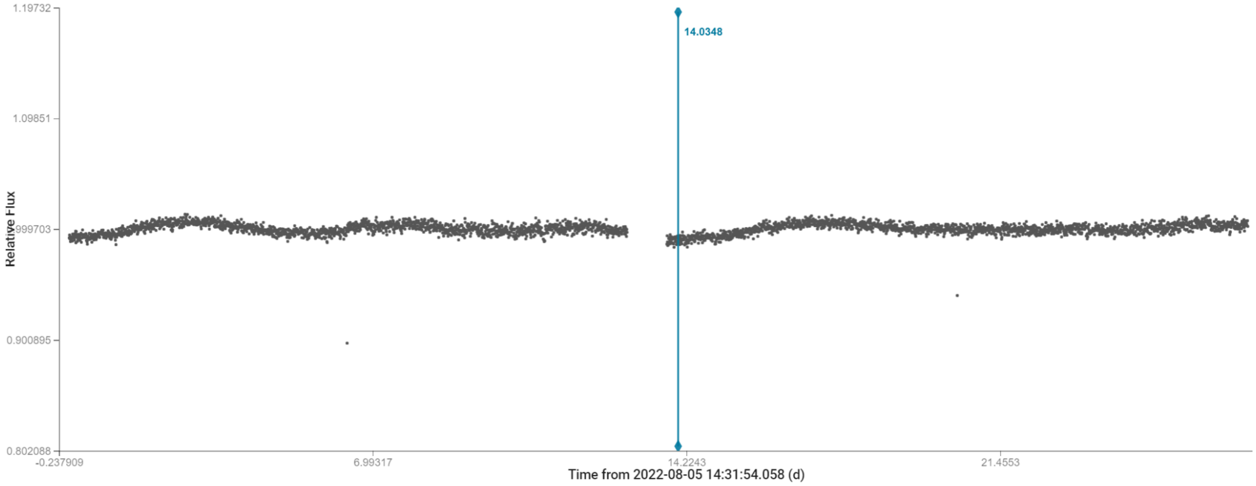

Figure 1: Light curve of TOI 5907.01 as observed by TESS

2.3

We observed TOI 5907.01 on June 20th, 2024 at the George Mason University observatory. A total of 204 exposures were taken of TOI 5907.01 by the GMU telescope, but only 166 were suitable for data analysis due to some streaking and blurriness. The observation of TOI 5907.01 started at 22:55 and ended the next day at 4:30. TOI 5907.01 was observed for 0.796 hours with an exposure time of 85.000 seconds. An R filter was used during observation as well. The RA for TOI 5907.01 was 21:00:52.781, and the Dec was +17:06:59.14.

Section 3: Analysis

In Section 3.1 we present the tools used to analyze the TESS light curve of TOI 5907.01. In Section 3.2, we present our analysis of the ground-based light curve using AstroImageJ.

3.1

A light curve file of TOI 5907.01 was not available for us to download off of the MAST Archive, but a feature on the archive allowed us to visualize the light curve using LCviz, a tool designed for light curve visualization and analysis that utilizes Jupyter Notebook (lcviz.readthedocs.io/en/latest/#).

3.2

AstroImageJ (AIJ), is an ImageJ software meant for data reduction and analysis in astronomy (www.astro.louisville.edu/software/astroimagej/). In order to generate a light curve in AIJ, we first needed to complete the data-reduction and plate-solving of our darks, flats, and sciences to get rid of any artificial interference with our data. We also used a local version of Astrometry.net, ansvr, to speed up our plate-solving process (www.adgsoftware.com/ansvr/).

We then selected the “Aperture Photometry Tool” button on the AIJ toolbar and clicked on our target star in the first science image of the stack of the 166 total images. After selecting our target star, we used AIJ’s “Plugins” and “Astronomy” function to generate TOI 5907.01’s seeing profile. The seeing profile was then used to ascertain its aperture size and annulus sizes, where the source’s radius is the aperture size, and the background’s inner and outer radii are annulus sizes.

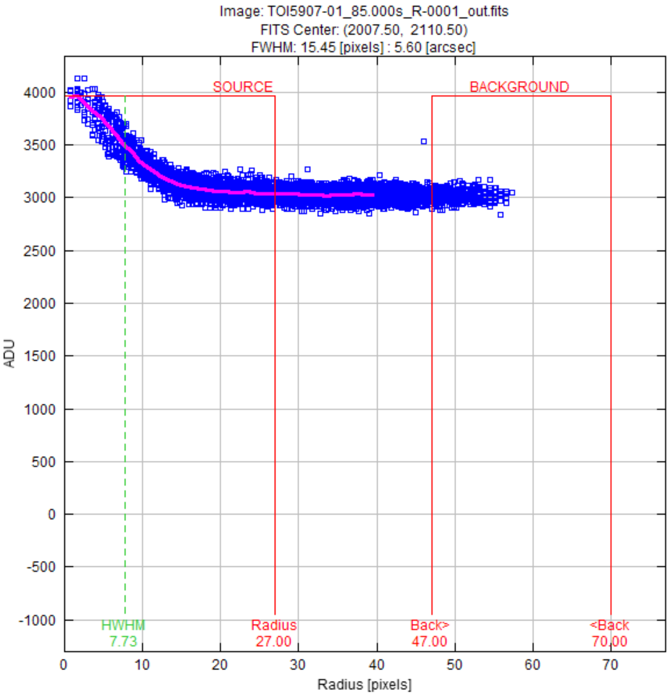

Figure 2: TOI 5907.01’s seeing profile

We began multi-aperture photometry by creating a temporary 2.5’ circle around our target star. Then, we imported TOI 5907.01’s Gaia stars .radec file. The 2.5’ circle works in combination with the Gaia stars during a later step in our analysis where we check for any NEBs to rule out a false-positive result.

Following the placement of the Gaia stars, AIJ was able to successfully perform multi-aperture photometry. Many reference stars were generated from this process, but we selected only the reference stars which were closest to our target star in the case that they might have been out of sight in later images. Following the selection of the reference stars, a measurement table was generated by AIJ which would be used to create the light curve plot of our target star and reference stars.

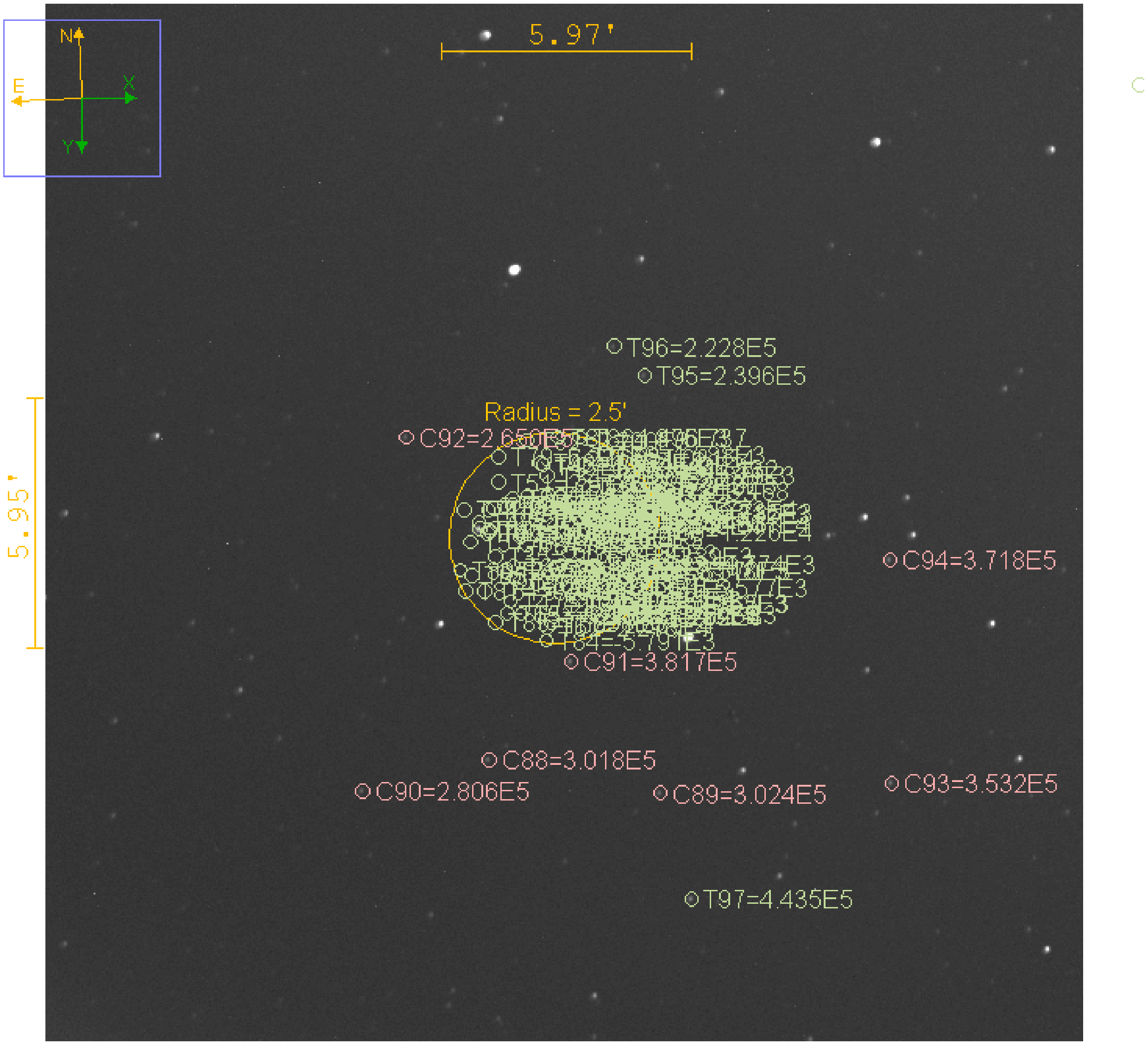

Figure 3: Field of view image with Gaia stars (green) and reference stars (red)

To turn the data in the measurements table into a light curve plot, we first downloaded the default template from AstroDennis (www.astrodennis.com/). Then, we opened the template in AIJ, to which our plot settings were automatically updated to follow the TESS/K2 reporting guidelines.

Following that, we manually imputed every other field necessary for making the light curve plot, such as the title, subtitle, and the known transit information for TOI 5907.01. We plotted all of the reference stars we selected earlier to check for scattering, and then chose only two to be featured in the light curve plot as reference light curves to that of TOI 5907.01.

Section 4: Results

The results from the AIJ light curve extraction (shown in figure 4) display a transit within the predicted ingress and egress times (shown clearly in red). No detrending parameters were used on this light curve plot, as none of them substantially reduced the plot's RMS.

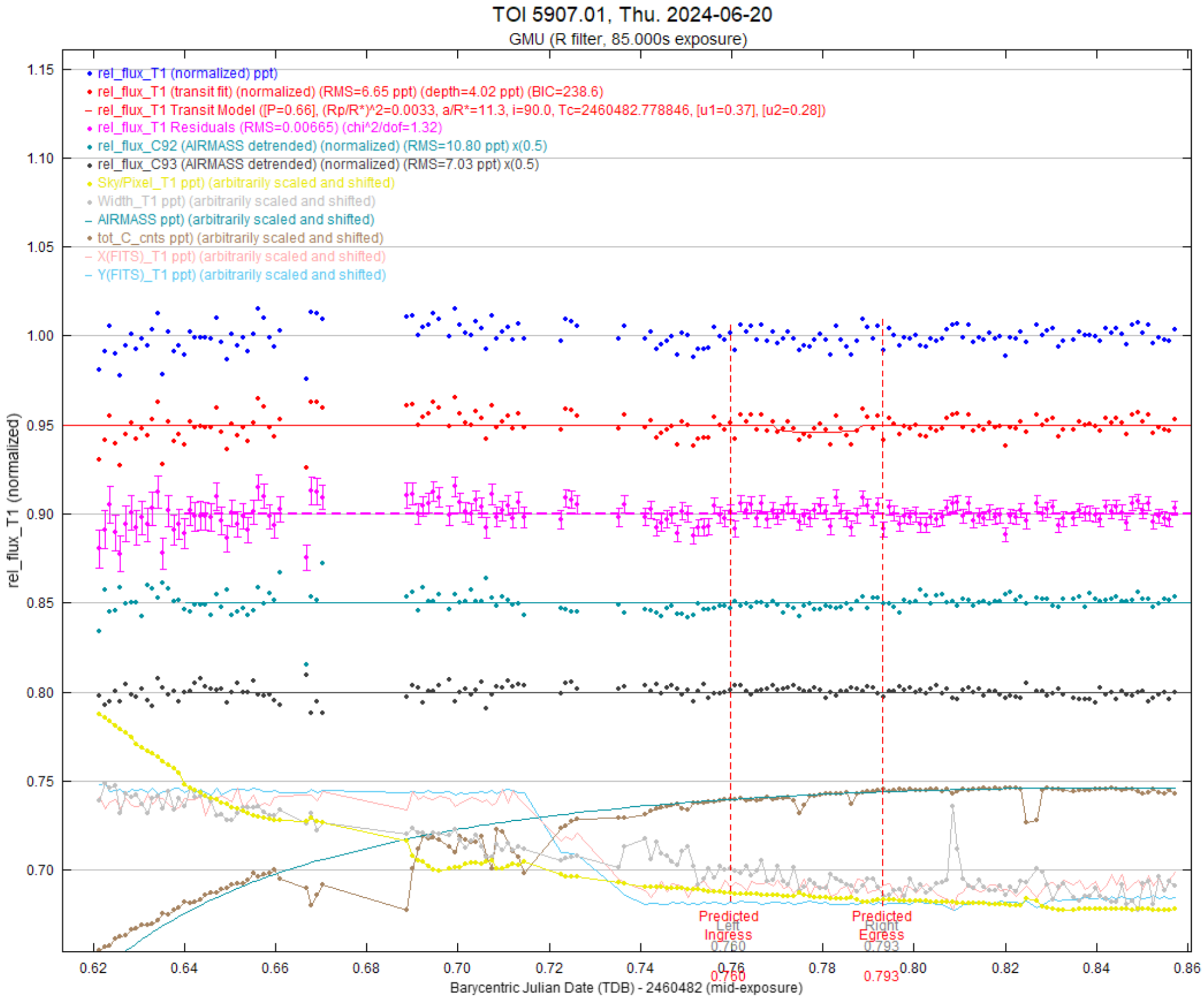

Figure 4: Light curve plot of TOI 5907.01 (blue, red, and residuals in magenta) and two reference stars (teal and dark gray)

The early gaps in the graph come from when we removed 38 exposures due to streaking and blurriness, but there is no interference from that within the time of the transit.

We then compared the light curve of TOI 5907.01 to its reference stars displayed on the bottom of the graph, plotted as teal and dark gray dots. The reference stars on the plot serve as control light curves, and when compared to the reference stars, the faint transit shown in the light curve of TOI 5907.01 is more clear.

Following the creation of the light curve plot, we conducted a NEB check to see if any NEBs could be the cause of our transit event. AIJ was able to create a NEB search report and plot using the Gaia stars imported earlier onto our image stack, the results of which will be discussed later in this paper.

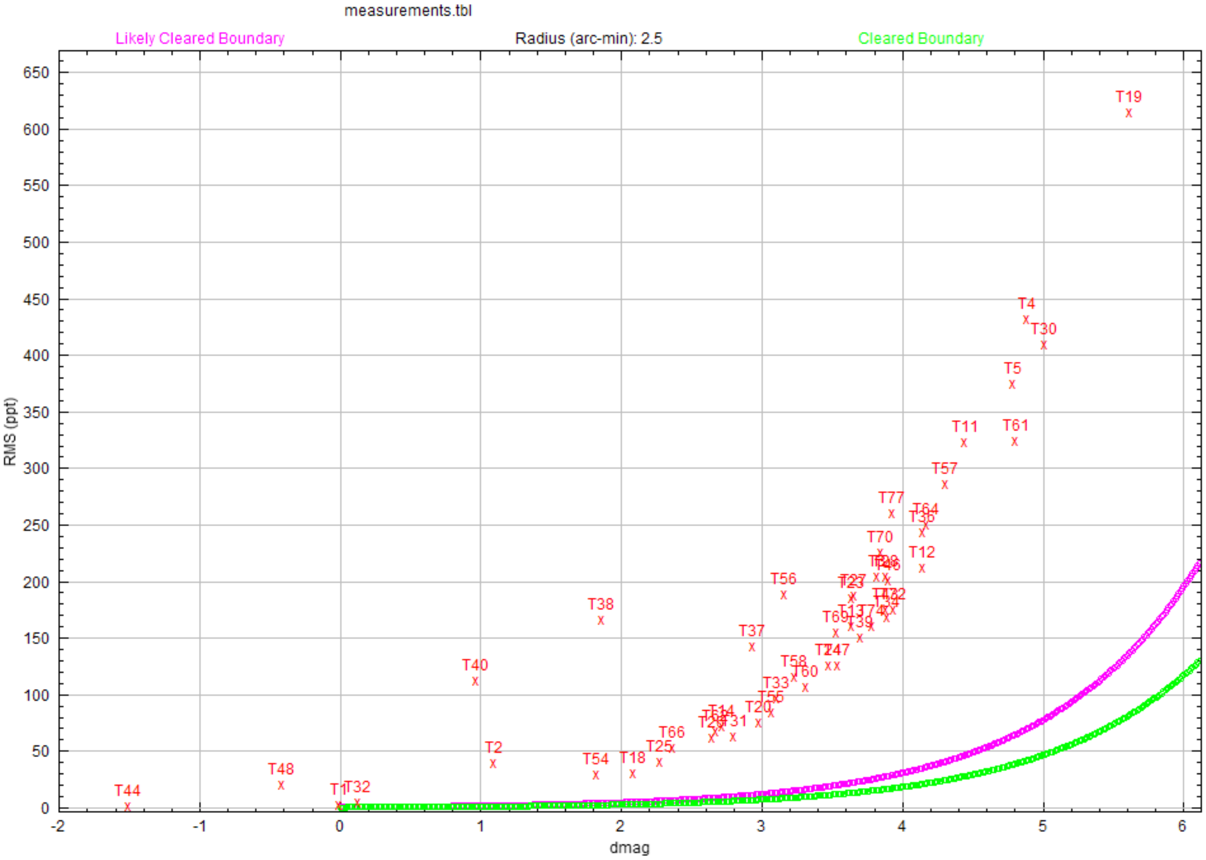

Figure 5: RMS vs dmag plot produced by the AIJ NEB check

Section 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

First, we assessed the goodness of fit for our model. The chi-squared value gives us an idea of how much the data differs from the model relative to the uncertainty to the measurements. If the chi-squared value is greater than one, the observations differ from the model more than the uncertainties. Our chi-squared value was calculated by AIJ, but the formula is as follows:

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

Our chi-squared value was calculated to be 213.0158, however, the chi-squared value can be divided by the degrees of freedom to create a reduced chi-squared value, which in our case was a much more favorable output of 1.323080.

$$\chi_\nu^2 = \frac{\chi^2}{\nu}$$

Therefore, the goodness of fit for our model is well within an acceptable range.

Our light curve plot shows a planet transit depth of 4.02 ppt, a close match to the transit depth recorded in the Exoplanet Archive of 3.7 ppt ± 2.38 ppt. Furthermore, the duration of the transit on our light curve plot was 28 minutes and 25 seconds, or 0.474 hours. Compared to the transit duration from the Exoplanet Archive, 0.796 hours ± 0.417 hours, our transit duration is within the estimated time.

However, this is not a confirmation that TOI 5907.01 is an exoplanet. When a NEB check was conducted that would search for nearby eclipsing binary stars that may have been the source of the transit event seen on the light curve plot, the results were inconclusive. None of the stars imported from the Gaia Mission cleared the NEB check: 39 stars did not clear due to their flux being low, meaning that those stars did not get enough light for AIJ to confirm whether or not they were possible sources of a false positive. On the other hand, the remaining 47 simply did not clear and could not be ruled out as the sources of the transit. The results of the NEB check do not automatically indicate that there is a NEB, but rather that the possibility of a NEB cannot be ruled out. A reason for our inconclusive NEB check results may be the quantity of Gaia stars near TOI 5907.01 that needed to be cleared, and that multiple of these Gaia stars overlapped with TOI 5907.01's host star.

5.2

If the transit we detected is an exoplanet, AIJ estimated that TOI 5907.01 has a radius of 4.66 Rjp, meaning that the planet is over 4 times larger than Jupiter. Combined with its estimated temperature of 1963 K and orbital period of less than a day, TOI 5907.01 would be classified as a hot Jupiter (Fortney).

Section 6: Conclusions and Future Work

Our observations were inconclusive in determining if TOI 5907.01 was an exoplanet or not. Considering the inconclusive results from the NEB check, we can not confirm that TOI 5907.01 is an exoplanet, nor can we rule out the possibility of it being an exoplanet.

Therefore, more research is needed on TOI 5907.01 to validate it as an exoplanet. In the future, we suggest that a more powerful telescope is used to observe TOI 5907.01, along with longer exposure times and better observing conditions. These measures will likely improve the results of the NEB check, since so many of the nearby stars could not be cleared due to their low brightness. Furthermore, alternative methods of exoplanet validation like radial velocity measurements and spectroscopy should be used to perform more detailed false-positive analysis on TOI 5907.01.

In addition to more research, more work can be done with the data we collected to statistically rule out false-positives. ExoFAST is an astronomical tool designed to fit exoplanetary transits and ascertain the uncertainties in the data (Agol, et al. 1). ExoFAST could be used to rule out false-positives in our own data, but we also recommend that ExoFAST is used in future studies.

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