Draft version August 19, 2024
Typeset using LaTeX **twocolumn** style in AASTeX631

Ground-based Light Curve Follow-Up Validation of TESS Observations for Object of Interest TOI 5191.01

Maya Sompalli[1] and Dr. Peter Plavachan[2]

[1] *Irvington High School*
41800 Blacow Road, Fremont, CA 94539, USA
[2] *Department of Physics and Astronomy*
4400 University Drive MS 3F3, George Mason University
Fairfax, VA 22030, USA

ABSTRACT

The objective of this study is to determine whether TESS candidate TOI 5191.01 is a transiting exoplanet. The TESS faint star QLP search mission flagged the candidate on April 25, 2022, but it still required validation. We collected raw data from the 0.8m telescope at George Mason University in Fairfax, Virginia, then performed data reduction and plate solving using the AstroImageJ (AIJ) software to process the images and plot the light curve. We also conducted a non-eclipsing binary (NEB) check to rule out interference from another light source. To validate this exoplanet, we compared our calculations with previously collected data from the NASA Exoplanet Archive. However, due to imperfect weather conditions and data collection, we could not validate this exoplanet, and our analysis was inconclusive. For future work, we recommend gathering telescope data under clearer skies and using a more powerful, sharper telescope.

1. INTRODUCTION

January 9, 1992, marked a pivotal moment in astronomy: the first detection of an exoplanet. Since then, exoplanets—planets orbiting stars outside our solar system[1]—have fascinated scientists and the public alike. Over 5,000 exoplanets have been confirmed, with thousands more classified as candidates awaiting confirmation.

Researchers employ various methods such as radial velocity and direct imaging to discover exoplanets. In this paper, we focus on the transit method. This technique involves measuring the brightness (or flux) of a target star and identifying consistent dips in the graph that indicate an exoplanet passing in front of the star. These transits cause a temporary dimming of the star's light, which can be detected and analyzed to identify other characteristics of the exoplanet. NASA and other astronomical agencies deploy telescopes into space, equipped with powerful cameras and sensors to capture these brightness measurements. A prime example is the NASA TESS (Transiting Exoplanet Survey Satellite) mission, led by MIT. TESS surveys the sky in 26 sectors, spending 27 days on each sector during its two-year mission[2]. Since its launch in 2018, TESS has confirmed 542 exoplanets, with 7,208 candidates still awaiting validation[3].

Today, thousands of exoplanet candidates still require validation. With the knowledge that there are more planets than stars[4], and as advanced telescopes begin capturing light from distant galaxies, the number of potential candidates will only continue to rise. Papers like this one are crucial for covering all aspects of such analyses. On some occasions, it is possible to validate candidate exoplanets solely with TESS data. For instance, a team in Italy confirmed TOI-6883.01 using only information from the TESS mission[5]. Other times, even with ground based follow up observations, the validation will turn out to be probable but inconclusive, as shown in one paper published in the Journal of Astro-Scholars

[1] https://exoplanets.nasa.gov/what-is-an-exoplanet/overview/

[2] https://www.nasa.gov/wp-content/uploads/2016/07/tessscie ncewritersguidedraft23.pdf?emrc=94a59b

[3] https://exoplanetarchive.ipac.caltech.edu/

[4] https://www.nasa.gov/history/more-planets-than-stars-keplers-legacy/#:~:text=The%20Kepler%20mission%20enabled%20the, in%20the%20Milky%20Way%20galaxy

[5] https://iopscience.iop.org/article/10.3847/2515-5172/ad2c85/meta

Research[6] in 2023. Nevertheless, with over 7,000 candidates awaiting validation, follow up studies are critical.

Prior to this paper, two observations were made regarding TOI 5191.01. These included inconclusive light curves and speckle sensitivity curves obtained using two different telescopes: SOAR and MSU. Further details will be provided in subsequent sections. This is the first paper written on this particular candidate, underscoring the importance of its publication.

In this paper, we present follow-up observations of TOI 5191.01, which has an earth radius of 15.516 and an orbital period of 3.03 days. Our primary objective is to investigate whether the transit occurs on the expected star at the predicted time, with the anticipated duration and depth as identified by the TESS mission. We also utilize data from the Gaia mission, conducted by the European Space Agency. Gaia, equipped with a 1 billion-pixel camera, is designed to create a comprehensive 3D map of the stars in and beyond our Milky Way galaxy[7]. Using this data, we plot comparison stars, a process detailed in later sections.

This paper offers a brief overview of the analysis. For a more detailed exploration, please refer to the extended version available here: https://www.astro.louisville.edu/software/astroimagej/guide/AstroImageJ_User_Guide.pdf.

In Section 2, we present the characteristics of the object of interest and our observations from TESS and the George Mason University 0.8m telescope. In Section 3, we describe our analysis of the TESS light curve for TOI 5191.01 and explain how we obtained our ground-based light curve. In Section 4, we discuss the outcomes of our analysis. In Section 5, we interpret the data we collected. Finally, in Section 6, we conclude with our findings and recommend future work on this exoplanet candidate.

2. OBSERVATIONS

In Section 2.1, we present TOI 5191.01 and its exoplanet candidate properties, its host star properties from the TESS Input catalog in the NASA Exoplanet Archive, the Gaia mission, and other archival sources. In Section 2.2, we present the TESS sector light curve from the archive and its properties. In Section 2.3, we present a summary of the data collected with the George Mason University 0.8m telescope.

2.1. *Background Information*

TOI 5191.01 was part of the TESS faint star QLP search mission on April 25, 2022. Its host star, with an effective temperature of 8032.000 K—about 3000 K hotter than our Sun—is a class A white dwarf star[8]. The star has a stellar radius approximately 1.90 times that of the Sun and a mass 1.94 times greater. We used these values in our data analysis, along with over 500 comparison stars the software plotted using a subset of Gaia mission data.

2.2. *TESS Light Curve*

From the MAST Archive, we found the TESS sector light curve (Figure 1) displaying the latest curve of the star. We used LCviz to view the light curve, a tool designed for light curve visualization and analysis[9]. It shows a plot of the relative flux with respect to time in days. At a time of 13.7223, there is a break in data. Furthermore, there seems to be the same dip in the data around both 3.0 days and 21.0 days, indicating some possible astronomical event. Our mission is to confirm this candidate as an exoplanet.

2.3. *Speckle Sensitivity Observations*

TOI 5191.01 was the candidate of two speckle sensitivity observations that were then reported to the ExoFOP database[10]. Speckle sensitivity is a technique used to overcome the blurring effects of the Earth's atmosphere in order to achieve higher-resolution images and detect faint companions or features near stars and other astronomical objects. It involves taking multiple short exposures of an astronomical object and then processing them to achieve a higher-resolution image.

The first observation, conducted on May 25, 2022, by Stephen F. Austin State University, used the Southern Astrophysical Research (SOAR) 4.1m Telescope in Chile, producing a speckle sensitivity curve that revealed no significant stellar companions within 3 arc seconds of TOI 5191.01 (Figure 2). While the data showed a sharp decrease in sensitivity close to the star, indicating the technique's ability to detect faint objects nearby, as the separation increased, the sensitivity gradually declined, and no additional companions were identified. This suggests that the exoplanet candidate transit is not likely to be a result of unresolved binary stars. A more in-depth description of the SOAR telescope and its mission can be found on the SOAR website[11].

[6] https://www.dropbox.com/scl/fi/fmtrlgap3e1dxtp5of0db/1_16_SamJ_TOI3779.01.pdf?rlkey=18clgyj657ooaa3o6jnty4f6xdl=1

[7] https://science.nasa.gov/mission/gaia

[8] https://www.britannica.com/science/stellar-classification

[9] https://lcviz.readthedocs.io/en/latest/#

[10] https://exofop.ipac.caltech.edu/tess/target.php?id=359469754

[11] https://www.ctio.noirlab.edu/ atokovin/speckle/index.html

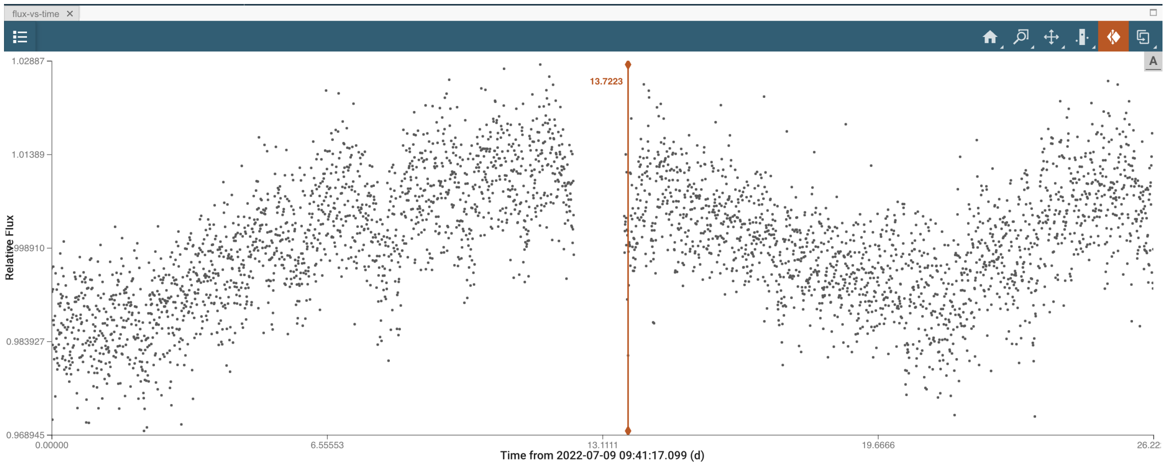

Figure 1. TESS Transit Light Curve from July 9, 2022.

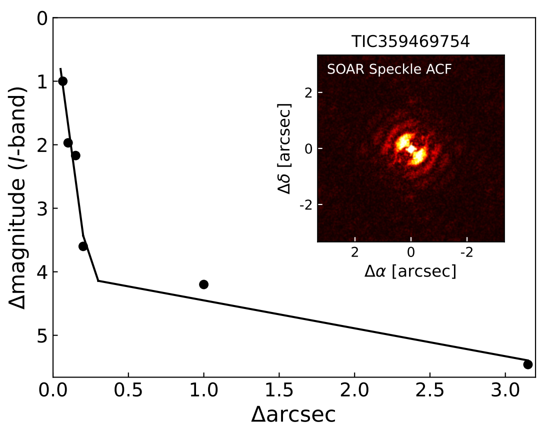

Figure 2. Speckle sensitivity graph by SOAR

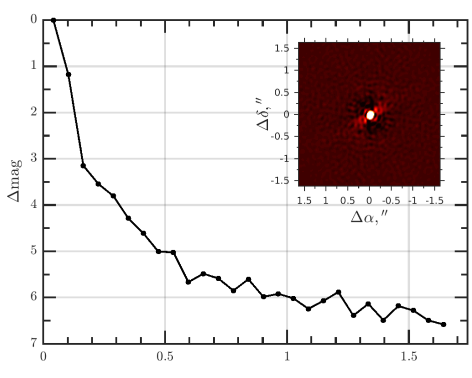

Figure 3. Speckle sensitivity graph generated by SAI-MSU.

The second observation, conducted more recently with the 2.5m Telescope at Caucasus Mountain Observatory of the Sternberg Astronomical Institute (SAI) MSU, presented similar results (Figure 3). The speckle sensitivity curve shown by SAI's team shows that there is no evidence of close stellar companions. While these observations do not confirm the presence of an exoplanet, they help rule out the possibility of a false positive due to a nearby star. Nevertheless, the conclusiveness of other tests, like a NEB check, using a ground-based data set is necessary to determine the nature of TOI 5191.01.

2.4. *Telescope Observation*

On June 27th, 2024, we observed TOI 5191.01 using the 0.8m telescope at George Mason University. Using the R filter, we aimed the GMU telescope at the right ascension (RA) and declination (DEC) coordinates of 19:26:16.221 and +18:59:43.03, respectively. Our observation period began at 23:21 and concluded at 03:02 on June 28, 2024. We compiled 10 flat files and 10 dark files, each taken at an exposure time of 3 seconds, along with 179 science images stored as .fits files. Due to problems with star visibility and streaking, we discarded 70 defective science images, leaving us with 109 raw sciences to use in this study.

3. ANALYSIS

This section outlines the steps taken to derive the light curve from the collected telescope images. Section 3.1 covers the data reduction process, Section 3.2 describes the plate solving procedure, Section 3.3 details the generation of the measurement table, and Section 3.4 explains the configuration of the light curve.

3.1. *Data Reduction*

The first step for turning science images into a viable light curve is to perform data reduction with the flat and dark images. Flat images correct for pixel imperfections, while dark files, taken with the lens shut, account for thermal noise from the CCD. Science images, stored as .fits files, are images the telescope takes of the target itself. We subtracted the darks from the science and flat images to remove contaminants, smooth the background, and create master dark and flat files.

3.2. *Plate Solving*

After collecting the data and storing it in a manageable directory, we moved on to the plate solving. Plate solving is the process of aligning all the images using the RA and DEC coordinates so the target star is in the same spot in all the images. We used AIJ and a key from Astrometry.net to run the plate solving so we would not have to manually align the science images. Despite some images failing to plate solve, we had enough to proceed to the next step of generating a measurement table.

3.3. *Measurement Table*

Using the plate-solved images, we used the Aperture Photometry Tool to figure out the aperture and annulus size. We generated a seeing profile which indicated the radius and inner and outer radii. After saving the seeing profile (Figure 4) and identifying suitable aperture and annulus measurements, we conducted multi-aperture photometry, a process where you find the amount of light that is within a circular area around the target star[12]. We overlaid the Gaia file for TOI 5191.01 to create an image with 500 comparison stars of similar brightness and size (Figure 5). This process generated a measurement table, the light curve, and its setting panels.

[12] http://spiff.rit.edu/classes/phys445/lectures/photom/photom.html#:~:text=Aperture%20photometry%20is%20the%20measurement,pressing%20the%20%22a%22%20key

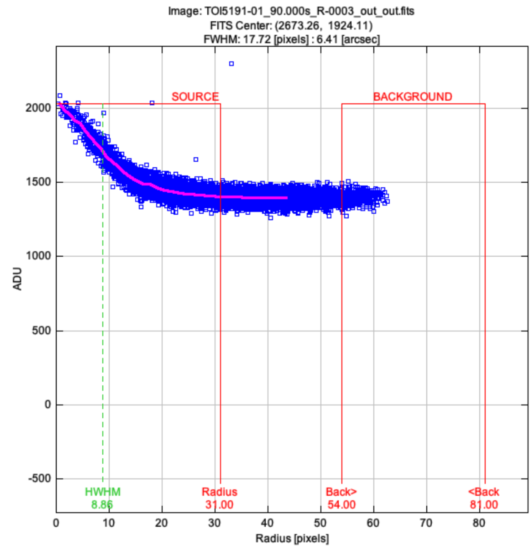

Figure 4. Seeing profile generated by AstroImageJ indicating the aperture and annulus size.

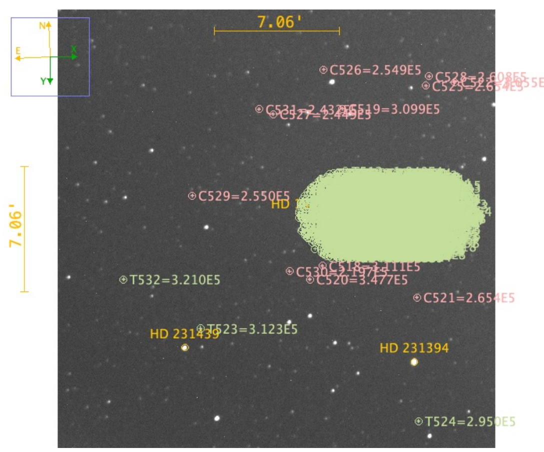

Figure 5. Gaia field image. Comparison stars in green.

3.4. *NEB Check and Light Curve*

For the light curve, we set a graph to show the time evolution of brightness flux. We also ensured that the predicted ingress and egress of the transit matched the times given in the NASA exoplanet archive. We then compared the data points of each comparison star to that of the target star to remove the outlier comparison star data points from the data set. Since the target star itself was faint, we conducted "Exhaustive Fit Optimization" to eliminate unsuitable comparison stars and determine the optimal configuration of the remaining ones. We then performed a NEB check to rule out the possibility that a nearby star was causing interference and affecting the light measurements (Figure 6).

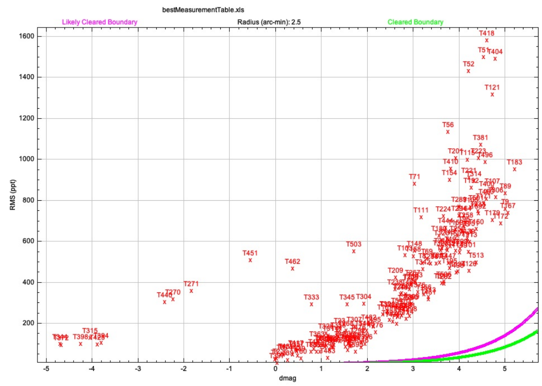

Figure 6. NEB Table generated by AIJ. All stars not cleared.

At first, the light curve we generated was far too varied, with the error bars overlapping with both the target flux data as well as the comparison star data. In order to lower the root-mean square (RMS) and get the transit depth as close to the one given by TESS, we chose to detrend and scale the data by the AIRMASS, Width, and x_fits parameters. We shifted and scaled the data to display the transit with corresponding error bars and data points of comparison stars. The now-detrended parameters appear at the bottom of the final light curve (Figure 7).

4. RESULTS

In this section, we present the transit curve for TOI 5191.01 (Figure 7) and our statistical analyses for this candidate exoplanet (Table 1).

Parameter	Value
RMS (ppt)	16.367
Depth (ppt)	18.44
Duration (days)	0.132
Chi^2	121.4457
DOF	78
P-Value	0.0012

Table 1. Calculations generated by AIJ for the observed transit.

5. DISCUSSION

In this section, we present our interpretations of our findings and our statistical analysis.

To determine whether TOI 5191.01 could be a valid transiting exoplanet, we conducted both qualitative and quantitative analyses. As shown in Figure 7, there is a clear transit, suggesting the possible existence of this exoplanet. Additional factors also needed to be considered. First, we detrended the data using three parameters to reduce the RMS value, as shown in Table 1. A lower RMS indicates a better fit of the data, with an ideal RMS being below 5 ppt. After detrending, our RMS value was 16.367 ppt, which is significantly higher than desired.

Error propagation is the process of finding the uncertainty of a given data set given the uncertainties of the individual data points. AIJ performed the error propagation calculations to give us the final values shown in Table 1.

Next, we performed a chi-squared goodness-of-fit test to assess how well the data aligns with the expected light curve transit. AstroImageJ calculated a chi-squared value of 121.446, which is quite high. The equation is as follows:

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

The chi-squared value divided by the degrees of freedom (DOF) should ideally be close to 1 for a good fit, as this indicates that the observed and expected values are similar. With a DOF of 78, our chi-squared/DOF value was 1.56, which is relatively close.

Additionally, we obtained a p-value of 0.0012, suggesting a statistically significant fit and allowing us to reject the null hypothesis that there is no astronomical event. Overall, the calculations indicate that our analysis is reliable, despite some deviations from the ideal values.

While the calculations themselves seem valid, there are a number of external conditions to take into consideration as well as comparisons with previous TESS data collection. To begin, the recorded depth from this data analysis using AstroImageJ was 18.44 ppt, more than double than that of the TESS mission, which recorded a depth of 6.7 ppt. Given that TESS has a much more powerful camera for capturing transit data from space, the depth measurements we obtained may be inaccurate.

Similarly, the expected duration was 3.669 hours, whereas the transit duration calculated from our model was 3.173 ± 0.375 hours—close, but not close enough. Moreover, the NEB check we performed turned out to be inconclusive. All 513 stars in the NEB check did not meet the flux threshold, resulting in the message "Not Cleared - flux too low." Therefore, we cannot confirm the presence of non-eclipsing binary star signals. One likely reason for the NEB check result is that the nearby stars are all fainter than the target star. It is possible that the telescope did not receive enough light from many of the nearby stars to achieve a clear RMS value.

The most important factor to consider, however, is the process of data collection. On the day of data collection, the weather was less than ideal, with cloudy skies and

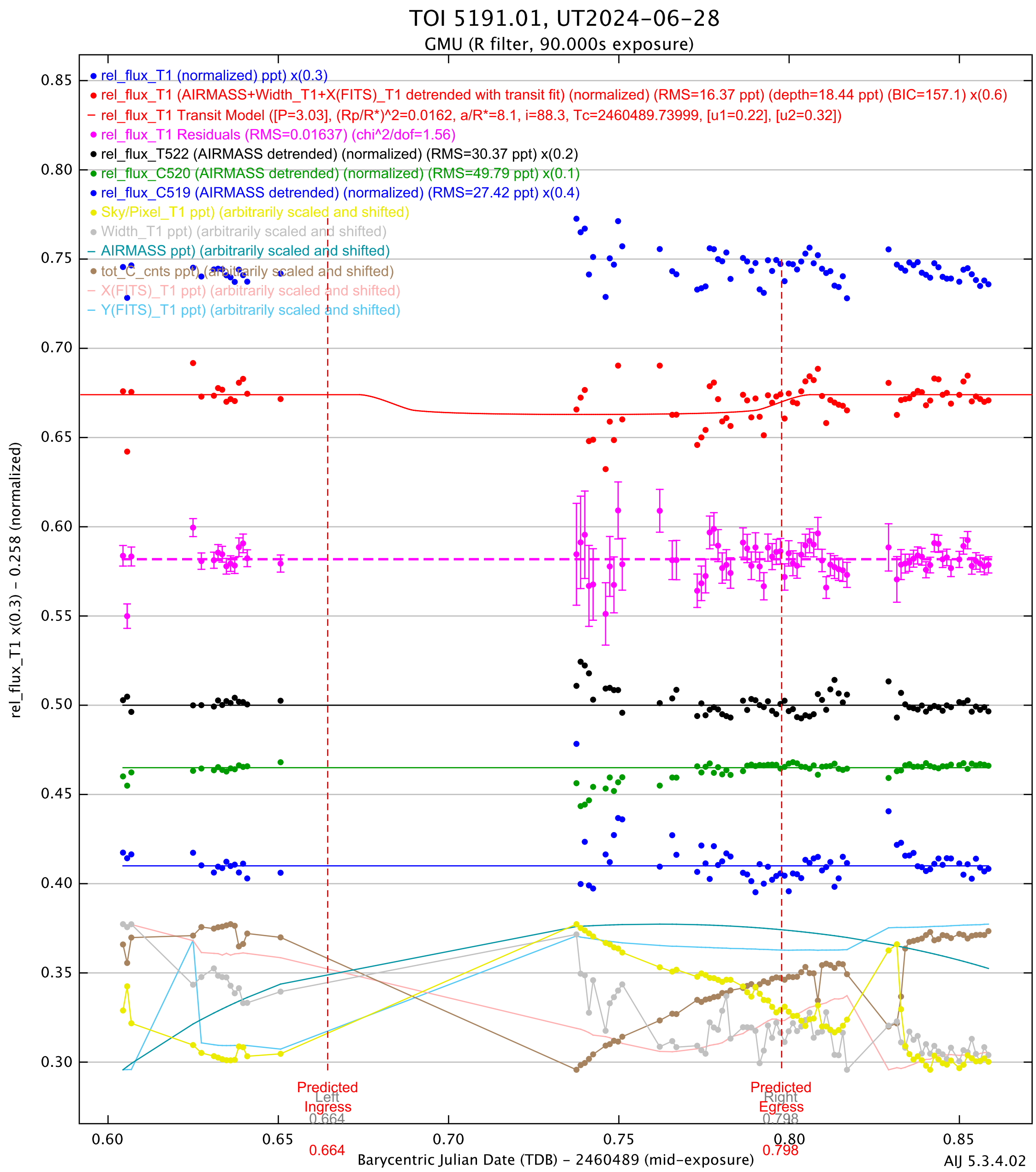

Figure 7. Transit light curve for TOI-5191.01. Transit line is shown in red. Comparison stars T522, C520, and C519 are shown in black, green, and blue respectively.

high humidity affecting the telescope's accuracy, compounded by possible scratches on the lens. We discarded over 70 bad science images, resulting in a huge gap in data, as can be shown in Figure 7. Therefore, our light curve and its resulting parameters are inconclusive.

6. CONCLUSIONS AND FUTURE WORK

Due to poor weather conditions and the characteristics of the target star itself, our follow-up observations have proven to be inconclusive. We are unable to determine whether the inconclusive results are due to a non-eclipsing binary star system or an actual planetary transit. For a valid transit detection, further detailed investigations are required, particularly improved data collection under more favorable weather conditions. A comprehensive NEB check could be achieved through deeper observations using a larger, more precise telescope. If a true transit is detected, subsequent research will have to focus on the properties of the exoplanet, including atmospheric chemistry and other key characteristics.

7. ACKNOWLEDGEMENTS

We would like to thank Dr. Peter Plavchan, along with Kevin Collins, Owen Alfaro, and S Falgiano, for guiding us through this study, providing essential resources, and enabling us to contribute to the understanding of exoplanetary systems.

This paper includes data collected by the TESS mission. Funding for the TESS mission is provided by NASA's Science Mission Directorate. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts. Furthermore, this work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos/.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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