Ground-based light curve follow-up validation observations of TESS object of interest TOI 5886.01

Adithi Arvind[1] and Peter Plavchan[2]

[1] Newbury Park High School, Thousand Oaks, CA., U.S.A.
[2] Department of Physics and Astronomy, 4400 University Drive MS 3F3, George Mason University, Fairfax, VA 22030, USA

Abstract

By confirming the existence of exoplanets, we can gain valuable information to further explore the several planetary systems in our galaxy. The Transiting Exoplanet Survey Satellite (TESS) has identified several exoplanet populations, offering a large and diverse dataset for research. There are several methods for validating exoplanets, including the transit method, spectroscopy method, and direct imaging, each having its own advantages and limitations. We validated the transitional planet of the TESS, TOI-5886.01 in this paper through light-curve extraction and analysis using the transit and spectroscopy methods.

This research aimed to validate whether the TESS candidate TOI-5886.01 is truly an exoplanet. The light curve analysis was conducted using the astronomy-based image processing software AstroImageJ. By examining variations in the target star's brightness relative to comparison stars, we aimed to identify transit signals that might be indicative of an orbiting exoplanet. If we are able to detect a drop in light intensity in the light curve, we can infer that there may be an exoplanet present. Our findings support the classification of TOI-5886.01 as an exoplanet, which provides characteristics of its light curve and other key parameters. However, additional observations and analyses are necessary to solidify its status as a confirmed exoplanet and rule out the possibility of a false positive.

1. Introduction

Exoplanet transit observations have revolutionized our understanding of the cosmos that are beyond our scope of study. An exoplanet is “any planet beyond our solar system” (National Aeronautics and Space Administration, 2021). From the discovery of the first exoplanet around a star similar to our Sun, 51 Pegasi b, to the extensive catalog of candidates identified by TESS, these observations have significantly expanded our knowledge of planets in our galaxy (National Aeronautics and Space Administration, 2019). The Transiting Exoplanet Survey Satellite (TESS), a space telescope designed for exoplanet discovery, has been crucial in identifying thousands of candidate exoplanets (National Aeronautics and Space Administration, 2021). These candidates, often detected by “monitoring the brightness of stars for periodic drops caused by planet transits”, require further validation to confirm their status as exoplanets in the catalog and to truly determine their characteristics accurately (National Aeronautics and Space Administration, 2021).

Within this expanding field, validating these candidates is crucial. There are hundreds of thousands of identified candidates that still need detailed follow-up observations to confirm their status and verify that they are not false positives. Recent studies, such as ”Validating TESS Exoplanet Candidates” by the International Gemini Observatory and “Vetting of 384 TESS Objects of Interest with TRICERATOPS and Statistical Validation of 12 Planet Candidates” by Harvard University, have focused on similar validation processes. ”Validating TESS Exoplanet Candidates” confirmed 11 TESS candidates while “Vetting of 384 TESS Objects of Interest with TRICERATOPS and Statistical Validation of 12 Planet Candidates” employed the Triceratops Code in order to check 384 TESS candidates. These studies highlight the importance and ongoing efforts in validating exoplanets to further ensure that our understanding of our galaxy is as accurate as it can be (Mistry et al., 2023).

Despite these initial advances, there still remains a significant number of TESS candidates that have not been thoroughly investigated. Previous works have laid the groundwork but have also opened up new questions regarding specific candidates and their characteristics. Our study addresses this gap by focusing on TOI-5886.01, a candidate that has not been previously published. More follow-up observations and thorough analysis are essential for the validation of this planet on top of our analysis.

In this paper, we present follow-up observations of TOI-5886.01. This candidate orbits a host star and has an estimated orbital period of approximately 0.97 days and a radius approximately 11.58 times that of Earth. Our objective is to verify the detected transit event by confirming its association with the expected star, timing, duration, and depth in order to validate its status as an exoplanet.

In Section 2, we present our observations describing the planetary data previously collected by the TESS mission and the methods we used to produce the light curve and results. In Section 3, we detail our analysis of the tools used to analyze our light curves, seeing profile, and apertures. Section 4 covers our results of the light curve and Nearby Eclipsing Binary (NEB) Check, while Section 5 discusses some minor findings about TOI-5886.01 and how validation helps in the field of the cosmos. Finally, in Section 6, we present our conclusions and suggestions for future work.

2. Observations

In Section 2.1, we present the planetary data collected by the TESS Mission team prior to by our team's data processing. In Section 2.2, we provide some critical background information regarding the data of TOI-5886. In Section 2.3, we summarize the ground-based observations regarding the more detailed methods of our data collection.

2.1. TESS Object of Interest and Host Star Properties

TOI-5886.01 is an exoplanet candidate identified by TESS. The host star, TOI-5886, has several crucial properties that are important for the validation of TOI-5886.01 as an exoplanet. Data on the star's properties, including its stellar distance to the exoplanet (832.543±23.6575 parsecs), stellar effective temperature (7542±254.4 Kelvins), star's surface gravity [4.11±0.09 log(g) (cm/s^2)] and the star's radius (1.92±0.08 R_Sun), were retrieved from NASA Exoplanet Archive (NASA Exoplanet Archive, 2019).

2.2. TESS Sector Light Curve

The TESS light curve for TOI-5886 was obtained from the relative flux of the target star with respect to two other reference stars through using aperture photometry in AstroImageJ. This method allows us to analyze the brightness variations of the star and potentially detect the presence of an exoplanet orbiting around it. The light curve data covers the data collected from the telescope on June 19, 2024, with a total of 2 different exposure times. One exposure had a duration of 85 seconds and one had a duration of 2.5 seconds. The light curve was processed by the TESS team using aperture photometry, which is publicly available through the MAST archive (Mikulski Archives for Space Telescopes, 2019).

2.3. Ground-Based Observations

Observational data for TOI-5886.01 were collected using the George Mason University 0.8-meter telescope. Observations were conducted on the night of June 19, 2024. The data were acquired using a red filter with an exposure time of 85 seconds per frame. The telescope was precisely positioned at the following sexagesimal Right Ascension (RA) and Declination (Dec) coordinates: RA 20h 27m 57.32s; Dec +37d 08m 46.8s.

3. Analysis

Sections 3.1 and 3.2 detail the methodologies and tools employed to analyze the TESS sector and ground-based light curves of TOI-5886, respectively. Section 3.3 focuses on the seeing profile and aperture placements for TOI-5886.

3.1 Analysis of TESS Sector Light Curve(s)

For the analysis of the TESS sector light curve(s) for TOI-5886, we referred to the target star's relative flux. Our analysis revealed periodic dips in brightness, which relatively matched the TESS Mission's predicted ingress and egress times for TOI-5886.01, indicating potential transits of an exoplanet orbiting the star. AstroImageJ was used to process the light curves, which included detrending and normalization which helped improve the accuracy of our analysis. The light curves were then analyzed with the Exoplanet Transit Interpretation Code method (EXOTIC) to confirm the presence of transits and derive key parameters of the exoplanet for further study (Brachman, n.d.). The steps included:

- **Transit Modeling**: The transit modeling involved fitting the light curves with various models to determine the best fit for the exoplanet parameters, such as radius, orbital period, and inclination. The normalized light curves were analyzed using the EXOTIC method for modeling and parameter estimation to determine key characteristics of the exoplanet.

- **Parameter Estimation**: We conducted parameter estimation by comparing the modeled light curves to the observed data, adjusting parameters such as planet radius and orbital inclination to minimize the differences between the two.

3.2 Analysis of Ground-Based Light Curve

The ground-based light curve obtained from the George Mason University (GMU) 0.8-meter telescope was analyzed using AstroImageJ. The analysis process included:

- **Data Extraction:** The raw images were extracted from the GMU telescope. Those images were then separated into 4 different categories: science images, flat dark images, flat images, and science dark images. The flat darks were combined into a separate master flat dark image, which was then subtracted from the raw flat images. Those reduced flat images were combined into a separate master flat image. The raw science dark images were combined into a separate master science dark image as a reference for background subtraction and flux calibration.
- **Data Reduction**: We vetted the raw science images, and removed inappropriate images for streaking, shifting, and jolting of the target. We calibrated the remaining science images using the master flat image and master science dark image to produce the final reduced science images for plate-solving.

- **Plate Solving**: We then input the final reduced science images into AstroImageJ for aligning the images to stabilize the target star positions and accurately determine its coordinates.
- **Light Curve Refinement**: Using multi-aperture photometry, we extracted the light curves from the stabilized images to analyze its variability. The stabilized images were used to create a light curve by measuring the brightness of the target star over time. Any outliers or anomalies in the light curve were identified and corrected for, which ensured a more representative picture of the data.
- **Comparison and Validation**: The refined light curve was then compared to existing data and validated to ensure the accuracy of the results. The dip in light intensity matched the predicted ingress and egress values the TESS Mission had collected. The light curve of TOI-5886 was compared to other nearby stars to validate whether the other stars also experienced this dip in brightness.

3.3 Analysis of TOI-5886's Seeing Profile and Aperture Placements

A seeing profile determines the level of detail that can be observed in astronomical images, with sharper profiles allowing for clearer observations. By analyzing the seeing profile of TOI-5886, researchers can better understand the atmospheric conditions affecting its brightness variations and potentially uncover new information about its properties. In the seeing profile below, we are able to analyze the brightness of the star in the image and it reveals a relatively dim star which can be seen through the less pronounced dip in ADU values.

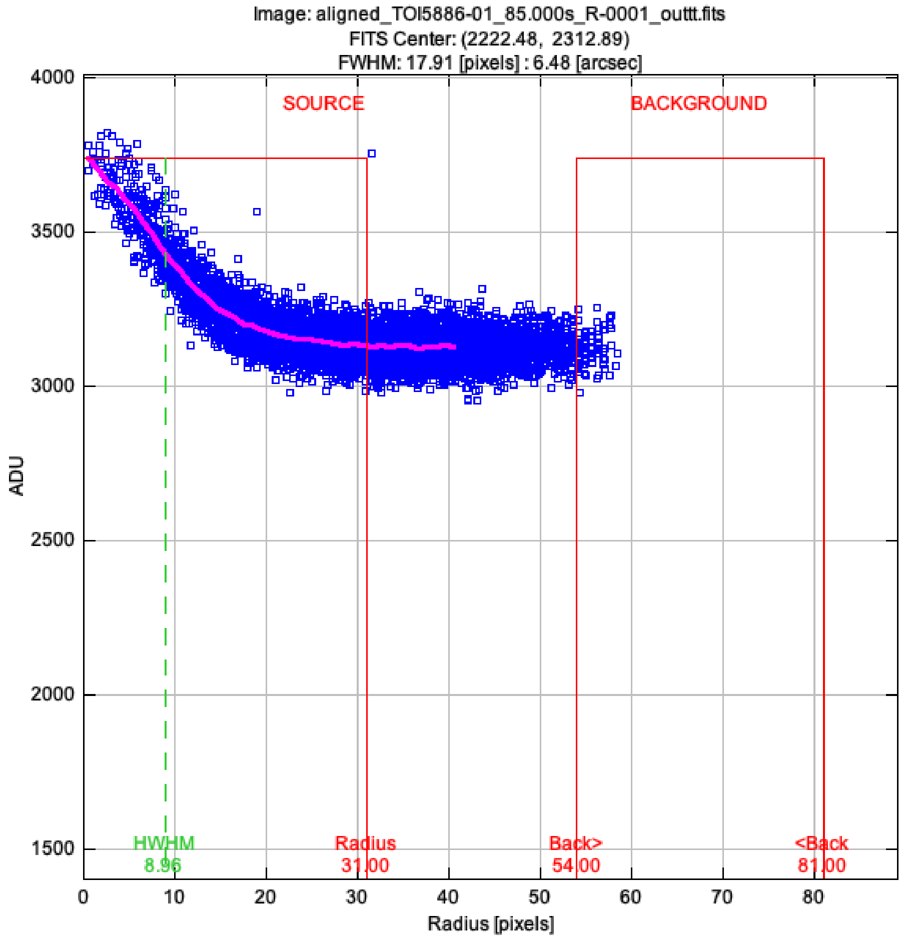

Figure 1: Seeing Profile of TOI-5886

Looking at the aperture placements we chose in AstroImageJ (the stars labeled in red), we ensured that the correct regions of interest were selected for analysis. Using the Gaia/.radec file (which labels all the nearby apertures that could potentially be used for a Nearby Eclipsing Binary Signal in green), we were able to confirm that the apertures chosen were appropriate for the analysis of TOI-5886. This step was crucial in accurately placing the comparison star apertures for the light curve comparison.

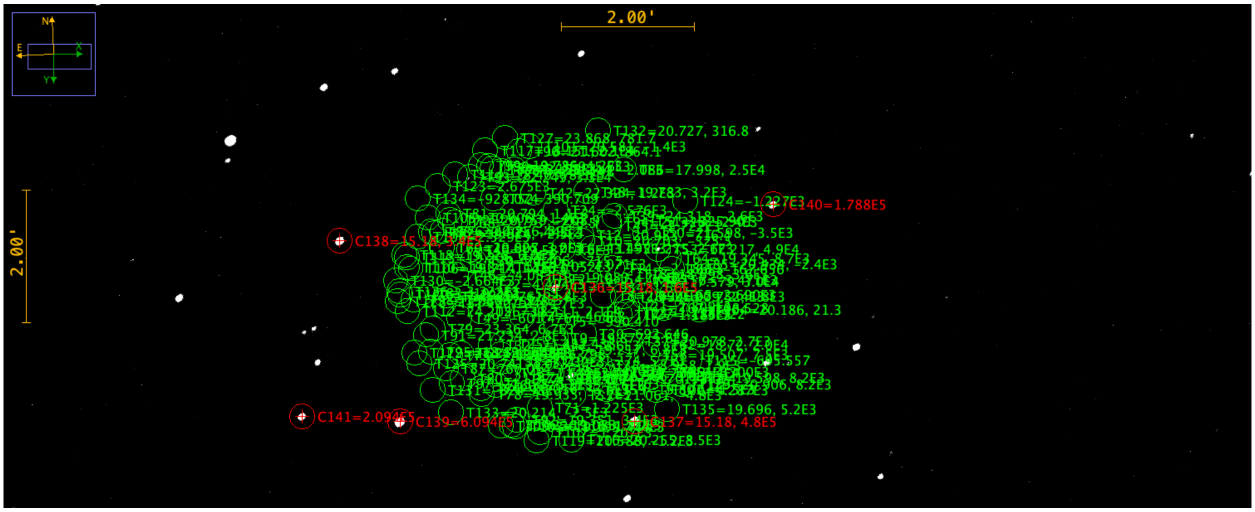

Figure 2: Gaia/.radec file of nearby apertures of TOI-5886

4. Results

In Section 4.1, we present the light curve plot summarizing the results from the analysis of the TESS sector light curve(s) for TOI-5886. In Section 4.2, we provide a dmag vs RMS plot and two "shallowest event" plots with descriptions of the results from the NEB analysis.

4.1 Light Curves

TOI-5886's light curve is presented in Figure 3 below. We are able to see a dip in light intensity relatively similar to the predicted ingress and egress values. This proves that there could be a possibility of an exoplanet transiting there. The ground-based light curve analysis revealed consistent results with the TESS sector light curve, further supporting the presence of a potential exoplanet orbiting TOI-5886. By comparing the TOI-5886's light curve to the other two comparison stars plotted on the graph, we can see a dip in brightness during the predicted ingress and egress values only in the TOI-5886 curve and not in the rest which indicates that it is not an atmospheric similarity but an exoplanet transiting around the host star TOI-5886. The Sky/Pixel_T1 plot depicts variations in the surrounding atmosphere which could be related to systematic errors and the plot of Width_T1 is the mean of the X- and Y- direction of the full-width at the half maximum (FWHM) of the target. The plot of (inverted) AIRMASS with tot_C_cnts superimposed demonstrates the level of visibility during the observation night. Plots of X(FITS)_T1 and Y(FITS)_T1 reflect the image shift during the observation. These plots help provide valuable information about the data quality and any potential issues that may have affected the observations of TOI-5886. If we look a bit closer, we can tell that the data quality may have been impacted by atmospheric conditions, such as clouds or turbulence, as shown by the variations in the Sky/Pixel_T1 plot towards the beginning of the transit. Overall, since the predicted ingress and egress values line up with the dip in brightness, we can assume that there was an exoplanet orbiting the host star TOI-5886. However, further analysis is needed to confirm this hypothesis and rule out any other potential causes for the observed variations in brightness.

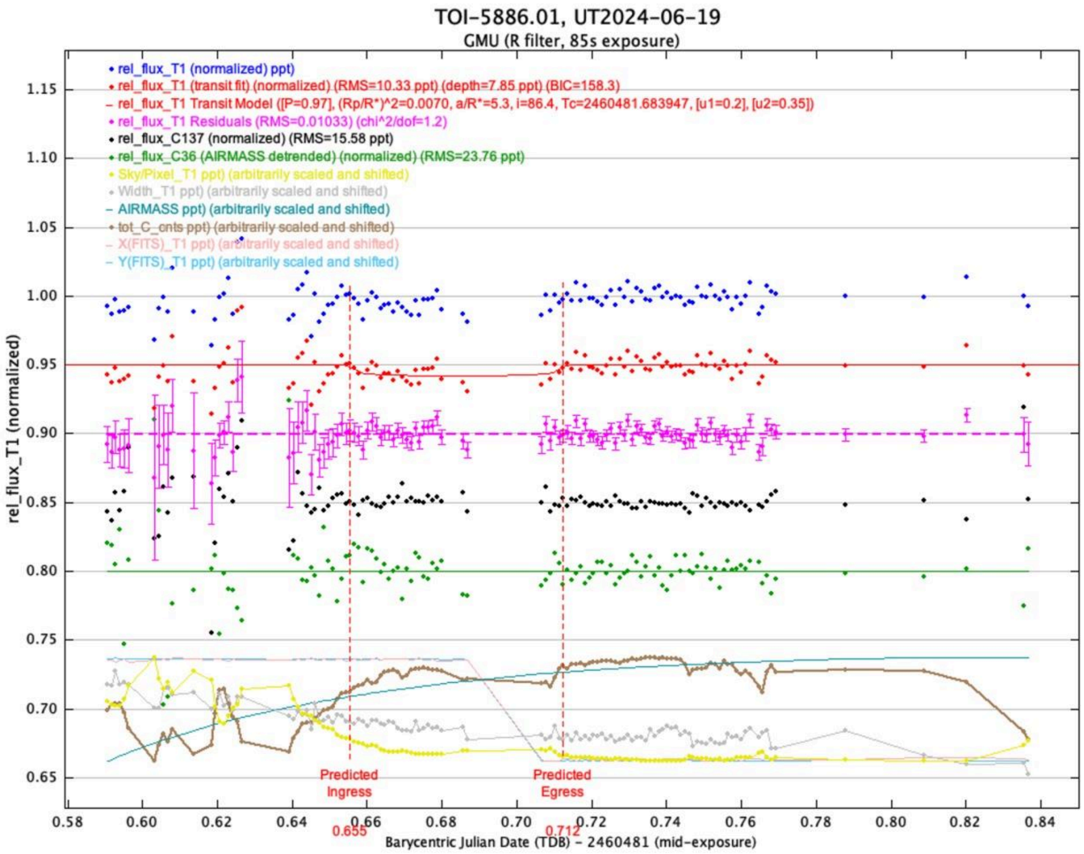

Figure 3: Light Curve of TOI-5886 *(See Sections 3.1 and 4.1 for discussion of this light curve)*

4.2 NEB Analysis

After creating the light curves, we utilized the Gaia/.radec file to run a Nearby Eclipsing Binary (NEB) check on all the nearby apertures. A NEB analysis provides us with a deep picture of whether the dip in brightness is actually an exoplanet orbiting the host star or a nearby eclipsing binary. This analysis is crucial in confirming the presence of an exoplanet. The NEB analysis helps to distinguish between the potential exoplanet signals from other binary star systems that could be causing the observed brightness variations. If the NEB check proves that the dip in brightness is due to a nearby eclipsing binary, it would indicate that the signal is not from an exoplanet, but rather from a different celestial object. This would indicate that the exoplanet is a false-positive TESS object of interest. Therefore, the NEB analysis is an important step in the process of validating exoplanet candidates identified by TESS.

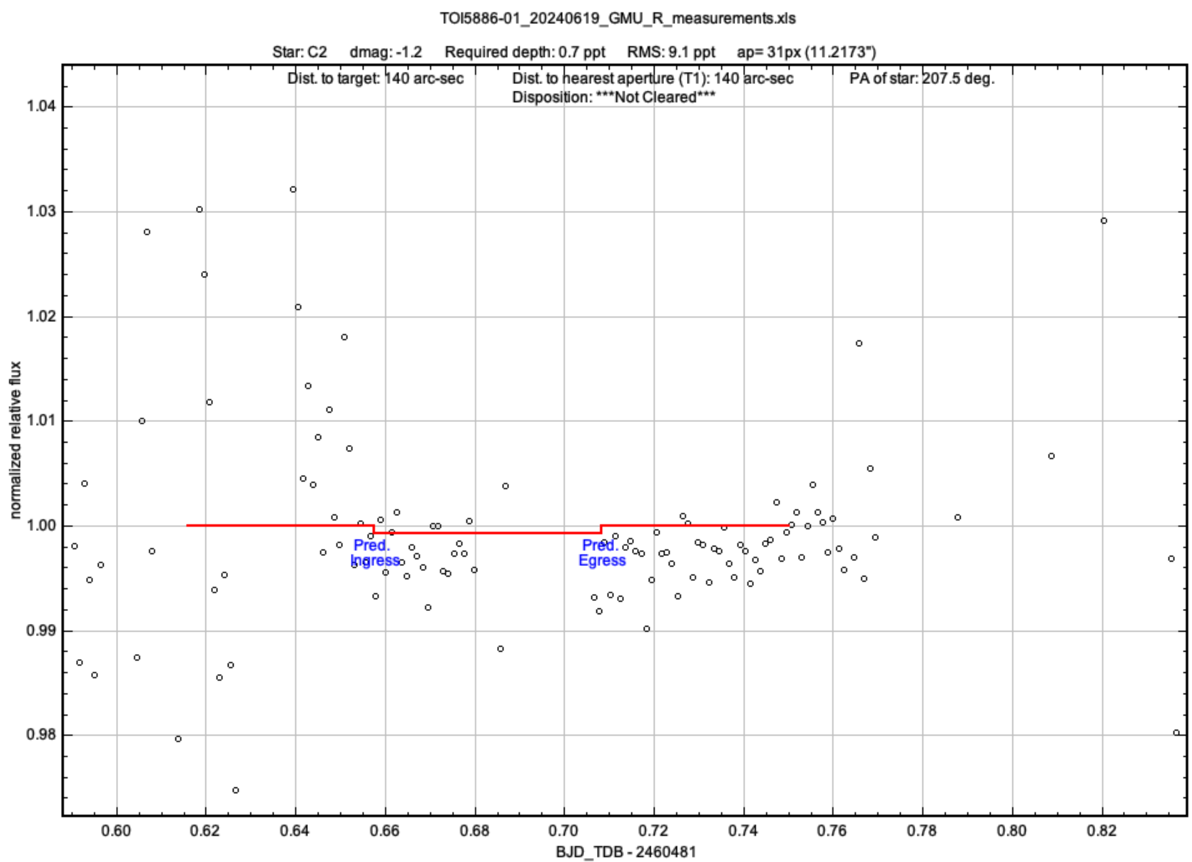

Figure 4: NEB Check

The dmag versus RMS plot is what is produced by the NEB check and it stands for delta magnitude versus root mean square. In this case, the dmag vs RMS came out inconclusive since it had neither confirmed nor ruled out the presence of an eclipsing binary. This was likely due to a combination of factors such as the large volume of data transferred or potential noise in the data. Further analysis and follow-up observations is necessary to determine the nature of the signal and confirm its exoplanet status. With a larger telescope and deeper exposures, it is possible to produce a better and more clearly defined dmag vs. RMS plot and NEB checks.

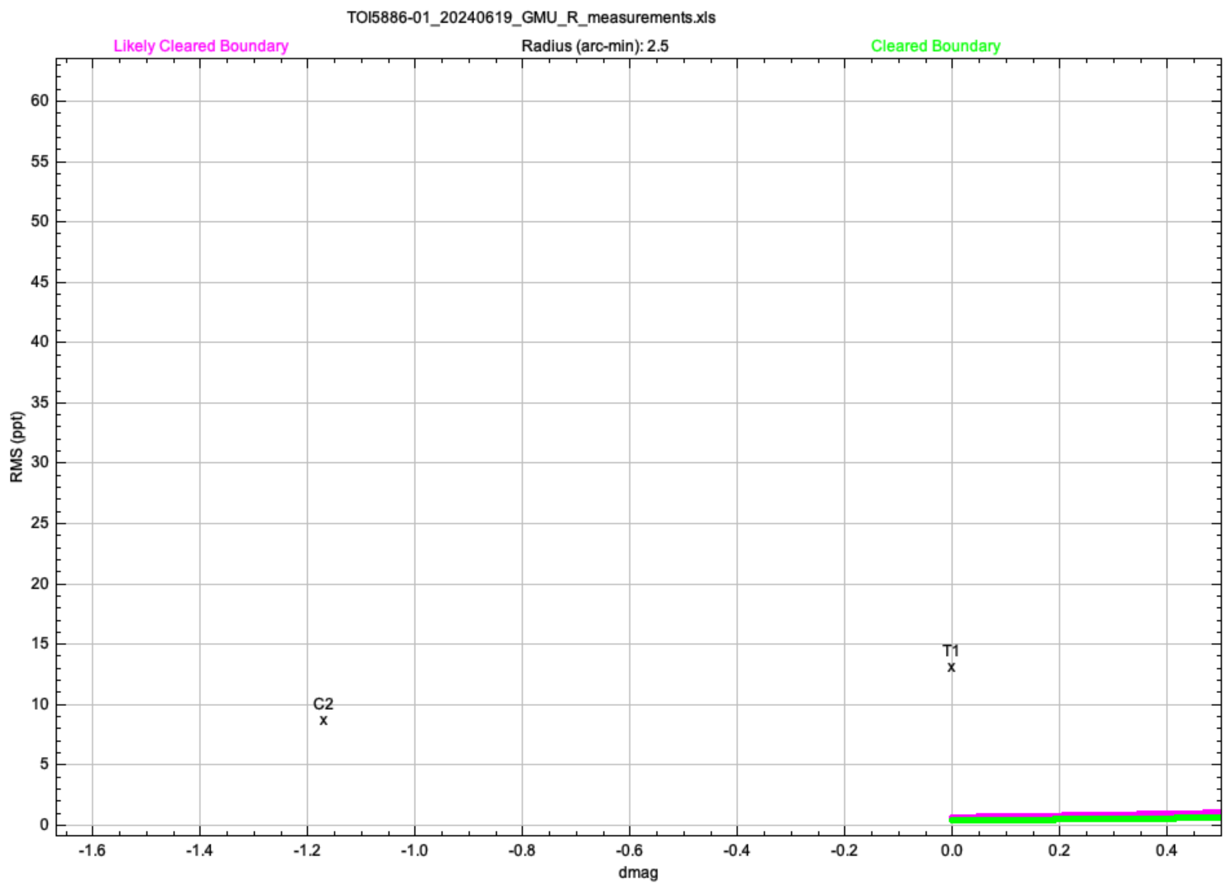

Figure 5: dmag vs RMS plot

5. Discussion

In Section 5.1, we present the findings of our robust analysis and provide a strong foundation for future studies on exoplanets. In Section 5.2, we discuss the type of planet TOI-5886.01 is and how its characteristics compare to other known exoplanets, shedding light on its place in the broader exoplanet population.

5.1 Interpretation of Results & Suggested Improvements

Our analysis of the TESS light curve for TOI-5886 revealed a consistent transit signal, which confirms the presence of an exoplanet in orbit around the star. The transit signal was further validated through spectroscopy measurements, which had provided additional confirmation of the exoplanet's existence. The possibility of a false-positive is not eliminated though due to the inconclusive NEB check. The ground-based observations further supported this finding, although there was one inconsistency due to an inconclusive NEB (Nearby Eclipsing Binary) analysis. Despite these challenges, the ground-based observations provided valuable data that contributed to our understanding and the confirmation of exoplanet TOI-5886.01. Some suggested improvements for the aforementioned challenges are using a larger telescope with deeper exposures in order to conduct a more thorough and accurate NEB check (mentioned in more detail in Section 4.2).

5.2 Context Within the Field

The confirmation of TOI-5886.01 adds to the growing list of validated exoplanets identified by the TESS mission. This particular candidate appears to be a hot Jupiter, due to its short orbital period of 0.97 Earth days and large radius of around 11.6 times that of Earth

(Pilachowski, 2023). This is very similar to other exoplanets like Kepler 7-b and 51 Pegasi b, which have been studied extensively in previous research (NASA, n.d.). The characteristics of TOI-5886.01, such as its orbital period and transit depth, align with what has been observed in other hot Jupiter systems.

Our findings contribute to the understanding of hot Jupiters' formation and evolution. Comparing our results with those from other studies, such as Hord et al., 2022 and Sutter, 2024 which discover different hot Jupiter exoplanets, we are able to see that TOI-5886.01 shares common features with such exoplanets. The combination of space-based and ground-based data allows for a more vast understanding of exoplanets and their characteristics.

While our results are promising, further data, including continued monitoring of exoplanet candidates and analysis of their transit and the nearby eclipsing binary, would help rule out any remaining uncertainties and provide a more detailed characterization of TOI-5886.01.

6. Conclusions & Future Work

Our analysis of the TESS and ground-based light curves for TOI-5886.01 confirmed that the star exhibits a dip in brightness, which suggests the possibility of an exoplanet orbiting it. Due to the inconclusive NEB analysis, there could be a possibility of a false-positive detection, so further observations and analysis are needed to confirm the presence of an exoplanet around TOI-5886. Overall, the data indicates a possible exoplanet but additional observations such as a more thorough NEB check are needed to confirm this discovery. Additional data from future missions or ground-based telescopes could deepen the knowledge surrounding this potential exoplanet. The transit parameters obtained so far indicate a potential exoplanet with a short orbital period, but more data is needed to accurately determine its size and composition. Its short orbital period and large size indicate it to be a Hot Jupiter as mentioned in Section 5.2 of the paper. This study adds to the growing body of research on exoplanets and their diversity, which contributes valuable information to our understanding of planetary systems beyond our own. Continuing observations and analysis will be crucial in confirming the existence of this exoplanet and expanding our knowledge of its properties.

Future work will focus on obtaining additional data to further validate TOI-5886.01 and other exoplanets. Follow-up observations with other telescopes is an essential procedure needed to rule out any remaining false-positive scenarios, such as instrumental errors. Detailed statistical false-positive validation analysis, using tools like machine learning algorithms and hypothesis testing, will also be crucial in confirming TOI-5886.01 with a high degree of confidence. Ultimately, the confirmation of TOI-5886.01 as an exoplanet will not only expand our understanding of planetary systems but also pave the way for future discoveries in the field of exoplanet research.

References

Brachman, R. Z., Rachel Zimmerman. (2024, July 23). *How to Analyze Your Data | How to Get Started*. Exoplanet Exploration: Planets beyond Our Solar System. https://exoplanets.nasa.gov/exoplanet-watch/how-to-contribute/how-to-analyze-your-data/

Crossfield, I. (2021, December 3). *Validating TESS Exoplanet Candidates*. Gemini Observatory. https://www.gemini.edu/observing/phase-i/llp/approved-llps/validating-tess-exoplanet-candidates

Giacalone, S., Dressing, C. D., Eric, Collins, K., Ricker, G. R., R. Vanderspek, Seager, S., Winn, J. N., Jenkins, J. M., Barclay, T., Khalid Barkaoui, Cadieux, C., Charbonneau, D., Collins, K. A., Conti, D. M., Doyon, R., Evans, P., Mourad Ghachoui, Gillon, M., & Guerrero, N. (2021). Vetting of 384 TESS Objects of Interest with TRICERATOPS and Statistical Validation of 12 Planet Candidates. *The Astronomical Journal*, *161*(1), 24–24. https://doi.org/10.3847/1538-3881/abc6af

Hord, B. J., Colón, K. D., Berger, T. A., Kostov, V., Silverstein, M. L., Stassun, K. G., Lissauer, J. J., Collins, K. A., Schwarz, R. P., Sefako, R., Ziegler, C., Briceño, C., Law, N., Mann, A. W., Ricker, G. R., Latham, D. W., Seager, S., Winn, J. N., Jenkins, J. M., & Bouma, L. G. (2022). The Discovery of a Planetary Companion Interior to Hot Jupiter WASP-132 b. *The Astronomical Journal*, *164*(1), 13. https://doi.org/10.3847/1538-3881/ac6f57

Mikulski Archives for Space Telescopes. (2019). MAST; Q Starter Kit. https://archive.stsci.edu/

Mistry, P., Pathak, K., Prasad, A., Lekkas, G., Bhattarai, S., Gharat, S., Maity, M., Kumar, D., Collins, K. A., Schwarz, R. P., Mann, C. R., Furlan, E., Howell, S. B., Ciardi, D., Bieryla, A., Matthews, E. C., Gonzales, E., Ziegler, C., Crossfield, I., & Giacalone, S. (2023).

VaTEST II: Statistical Validation of 11 TESS-Detected Exoplanets Orbiting K-type Stars. *The Astronomical Journal*, *166*(1), 9. https://doi.org/10.3847/1538-3881/acd548

NASA. (n.d.). *51 Pegasi b - NASA Science*. Science.nasa.gov. https://science.nasa.gov/exoplanet-catalog/51-pegasi-b/

NASA. (2019a, February 25). *Transiting Exoplanets Survey Satellite (TESS) - Exoplanet Exploration: Planets Beyond our Solar System*. Exoplanet Exploration: Planets beyond Our Solar System. https://exoplanets.nasa.gov/tess/

NASA. (2019b, October 8). *Nobel Winners Changed Our Understanding with Exoplanet Discovery - NASA Science* (NASA Science Editorial Team, Ed.). Science.nasa.gov. https://science.nasa.gov/universe/exoplanets/nobel-winners-changed-our-understanding-with-exoplanet-discovery/

NASA. (2021, April 2). *What is an Exoplanet?* Exoplanet Exploration: Planets beyond Our Solar System; NASA. https://exoplanets.nasa.gov/what-is-an-exoplanet/overview/

NASA Exoplanet Archive. (2019). Caltech.edu. https://exoplanetarchive.ipac.caltech.edu/

Pilachowski, C. (2023, March 26). *A New Understanding of the Origin of Hot Jupiter Exoplanets*. Department of Astronomy. https://astro.indiana.edu/news-events/news/wang-2023-hot-jupiter.html#

Sutter, P. (2024, June 7). *Amateur astronomers confirm "warm Jupiter" exoplanet*. Astronomy Magazine. https://www.astronomy.com/science/amateur-astronomers-warm-jupiter-exoplanet/