Ground Based Light Curve Follow-up Validation Observations of TESS Object of Interest (TOI) 5944.01

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Abstract

Exoplanets are planets that orbit stars external to the solar system. The Transiting Exoplanet Survey Satellite (TESS) is a space telescope designed by NASA's Explorer program with the goal of detecting exoplanets using the transit method. Objects that are potential candidates for exoplanet status are nominally marked as "Transiting Exoplanet Survey Satellite Object of Interest" or "TOI" for short. In this observation, TOI 5944.01 was analyzed. A few characteristics are known about TOI 5944.01, including having an orbital period of 5.94 days and a radius of 11.945 Earth radii. 194 exposures were taken by the GMU 0.8 m telescope, and after reduction, ground-based multi-aperture photometry was conducted to generate a light curve. The associated transit was analyzed at a predicted time, star location, and potential depth. Based on the analysis, the results are inconclusive but suggest that TOI 5944.01 could potentially be an exoplanet. However, further analysis is necessary.

1 - Introduction

Exoplanets are a relatively nascent, but significant field in astronomy. Their study began its rapid progression in 1992 when astronomers Aleksander Wolszczan and Dale Frail confirmed the first exoplanets, two rocky planets orbiting the pulsar PSR B1257+12 in the constellation Virgo [1]. Since then, the study of exoplanets has evolved, expanding our understanding of planetary systems and predictions of our own solar system's future [2]. Numerous techniques, methods, and technological advancements have emerged as means to detect exoplanets as well as their external celestial conditions.

On April 18, 2018, NASA launched the Transiting Exoplanet Survey Satellite (TESS), a space telescope outside of Earth's atmosphere designed to detect exoplanet candidates. TESS utilizes one of the most common and effective methods of exoplanet detection: the transit photometry method. [3] A transit refers to the periodic event of a planet passing between its host star and the observer. This event reduces the measured light flux from the star. Thus, obtaining light curves that measure such flux from the star with respect to time can serve as a mechanism to confirm the existence of exoplanets.

Potential candidates are named "TESS Object of Interests" or "TOIs" to indicate further, prospective analysis of the existence of a transit. Thousand of object candidates have been discovered since the launch of the space telescope [4]. This paper analyzes TOI 5944.01, the data for which was collected by the George Mason University 0.8m telescope on Monday, July 10, 2023 (2:50 UTC to 9:45 UTC). The TESS Input Catalog ID of our object of interest TOI 5944.01 is TIC 88101924. The Right ascension and Declination coordinates of TOI 5944.01 are 20:14:57.82s and +17:06:13.95s, respectively.

This paper aims to present a ground-based follow-up detailing the observations of TOI 5944.01. In **section 2,** we present observations from TESS and the George Mason University 0.8m telescope. In **Section 3**, we present our ground-based analysis of the light curve and potential transit. In **Section 4**, we present our light curve results. In **Section 5**, we present a discussion of the aforementioned results. In **Section 6** we present our conclusions and future work that we suggest to be done.

2 - Observations

In **Section 2.1**, we outline the exoplanet characteristics of TOI 5944.01 and detail its host star properties using data from the Gaia mission, TESS Input Catalog, and additional archival sources. **Section 2.2** provides a summary of observational data gathered using the George Mason University 0.8m telescope. **Section 2.3** consists of a comprehensive table of data regarding TOI 5944.01 and its host star.

2.1 - TESS Observational Data

As detailed above, the TESS Input Catalog ID of our object of interest TOI 5944.01 is TIC 88101924. The Right ascension and Declination coordinates of TOI 5944.01 are 20:14:57.82s and +17:06:13.95s, respectively.

TESS measurements indicate that the candidate exoplanet's transit midpoint is around 2459821.949 BJD, with an orbital period of approximately 5.94 days and a transit duration of about 2.479 hours. The exoplanet's radius is about 11.945 R_Earth, the transit depth is roughly 15160 ppm, and its insulation is approximately 133.7 Earth fluxes. The average temperature of the exoplanet is around 947 K. Furthermore, TESS data indicates that the distance between Earth and the host star is 593.58 pc. The star's effective temperature is approximately 5933 K, its log(g) is approximately 4.5 cm/s², and its stellar radius is approximately 0.97 R_Sun.

2.2 - GMU Telescope Observational Data

A total of 194 Science exposures were observed, each with 90 seconds of exposure time, starting from 2:50 UTC to 9:45 UTC. The George Mason University 0.8m telescope was used, which has a geographic location of -77:18:19.24 longitude, +38:49:41.5 latitude, and an altitude of 148.72. The telescope uses a red (R) filter to block out primarily blue surrounding light pollution.

2.3 - TOI 5944.01 Data Table

Parameter	Value
TESS Input Catalog ID (TIC ID)	TIC 88101924
TOI (TESS Object of Interest)	TOI 5944.01
Right Ascension	20:14:57.82s
Declination	+17:06:13.95s
Transit Midpoint (BJD)	2459821.949
Orbital Period (days)	5.94
Transit Duration (hours)	2.479
Exoplanet Radius (R_Earth)	11.945
Transit Depth (ppm)	15160
Insolation (Earth fluxes)	133.7
Average Temperature (K)	947
Distance to Host Star (pc)	593.58
Stellar Effective Temperature (K)	5933
Stellar Log(g) (cm/s²)	4.5
Stellar Radius (R_Sun)	0.97

3 - Analysis

In section 3.1, we will discuss the methods and tools that were utilized in the analysis of TOI 5944.01. In section 3.2, we will highlight the key steps and parameters necessary in the process of analyzing TOI 5944.01, in the pursuit of discerning a potential transit in the generation of a light curve. For the latter section, a discussion of AstroImageJ and EXOFAST (introduced in the former section) and their utility in this paper will be presented.

3.1 - Analysis Tools

AstroImageJ (AIJ) is an extension of the Java-based ImageJ software, designed specifically for astronomy. It provides a specialized environment for displaying and processing astronomical images, with tools for image calibration, time-series differential photometry, light curve detrending and fitting, and light curve plotting. It includes an interface for plate solving via astrometry.net. In this paper, AstroImageJ is used to reduce data, perform multi-aperture photometry, and ultimately generate a light curve for TOI 5944.01.

EXOFAST is a tool designed to analyze exoplanet transit data, either together or separately. It estimates the uncertainties and relationships between different parameters. In this study, EXOFAST is specifically used to predict key properties of TOI 5944.01 and its host star in conjunction with data analysis and collection performed by AstroImageJ.

Much of the preexisting data collected from TESS (mentioned above) was displayed on The Exoplanet Follow-up Observing Program (ExoFOP) website [5].

3.2 - Analysis Using AstroImageJ

Multiple crucial processes and steps were involved in the usage of AstroImageJ to generate TOI 5944.01's light curve.

First, in our data analysis, we began by downloading 238 images captured by the GMU telescope on July 10, 2023. This process involved the use of dark and flat images. Bias images were not used, as the darks included the necessary bias information.

The dark images were taken with the shutter closed at exposure times matching those of the flats and sciences. We combined the dark images into master darks, which were then subtracted from the corresponding raw science and flat images. Flats, taken with the shutter open and at an exposure time sufficient to achieve approximately 20,000 counts per pixel, were used to correct for distortions in the raw science images. These flats were combined into a master flat after subtracting the flat darks.

Second, we performed the data reduction of the science images by subtracting the science darks and dividing by the master flat. The final reduced and plate-solved science images were stored in a separate directory for further analysis. Throughout the process, all images were correctly grouped and inspected for any issues, such as streaking or misalignment. As such, there were only 194 images left post-data-reduction due to some faulty or unusable images that were not used for the aforementioned reasons. The reduced images were then ready for analysis.

Third, we plate solve the sciences, which refers to the process of assigning Right Ascension (RA) and Declination (DEC) coordinates to the objects in each image. Plate solving is paramount because it eliminates the need for manual alignment of images, which can save memory and streamline data handling, making further actions in this study far simpler. Plate solving also enhances precision when tracking key target stars, which be useful when performing multi-aperture photometry, especially in crowded fields or when images become misaligned. All our plate-solving tasks were completed successfully, providing us with the precise coordinates needed for our study.

Fourth, we imported the virtual stack of data-reduced and plate-solved science images and determined the appropriate aperture size for photometry. A measurement yielded an aperture radius of 25 pixels, with inner and outer annulus radii of 43 and 65 pixels, respectively **(Figure 1)**.

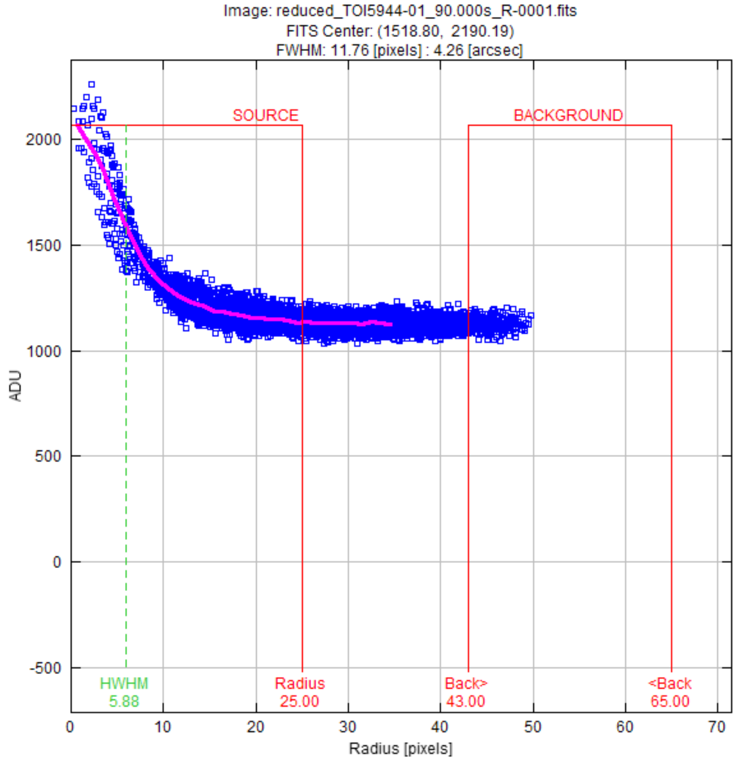


Figure 1: Seeing profile of TOI 5944.01 on AstroImageJ. An aperture radius of 25 pixels, with inner and outer annulus radii of 43 and 65 pixels, respectively is shown.

With the aperture and annuli radii set, we performed multi-aperture photometry. We placed a 2.5' circle around the target and overlaid a Gaia stars .radec file generated for the date of observation which was July 10, 2023. We then conducted multi-aperture photometry using the Gaia stars as reference points, selecting 12 Gaia stars and at least 10 other reference stars of similar brightness to TOI 5944.01 **(Figure 2)**.

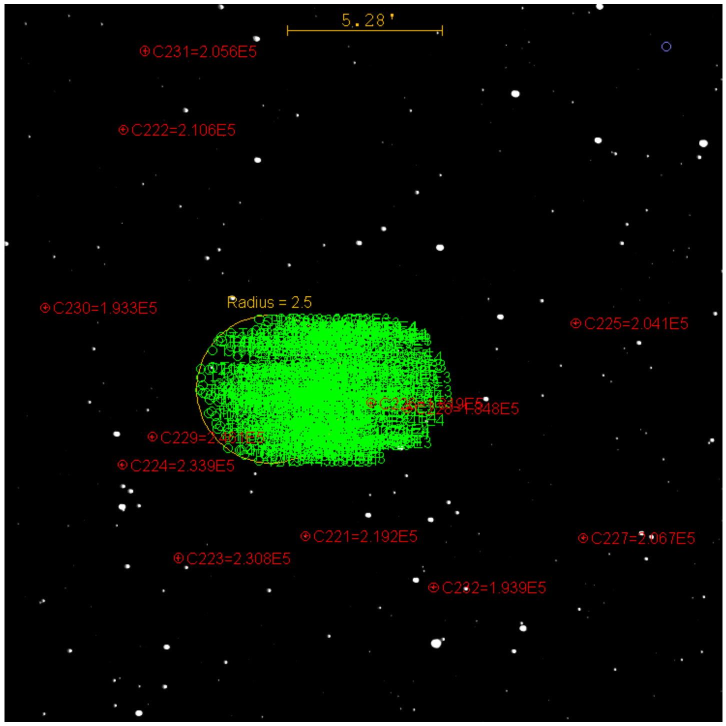


Figure 2: AstroImageJ aperture displaying TOI 5944.01 and reference stars

The multi-aperture photometry generated a measurement table containing the flux variations of TOI 5944.01, the Gaia stars, and the reference stars over time. This table will be used to plot the light curve.

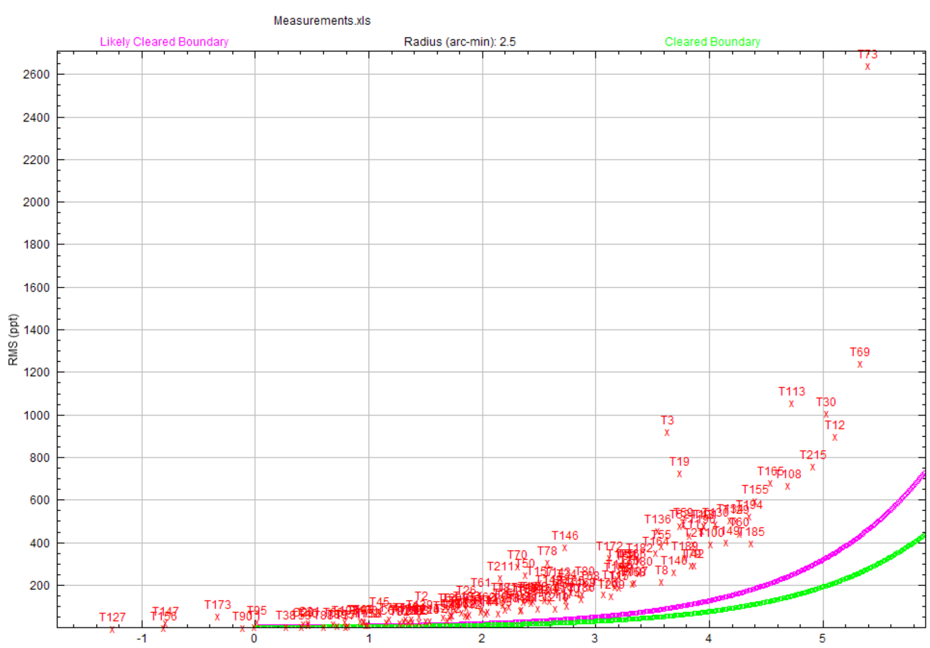
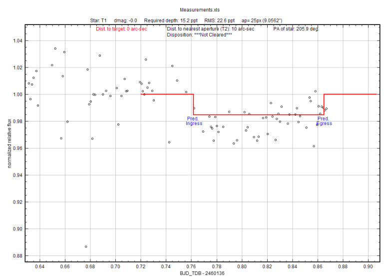
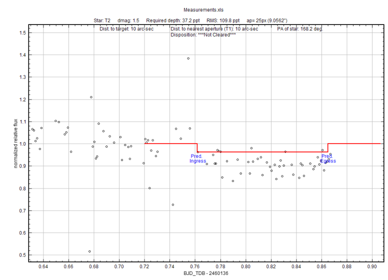


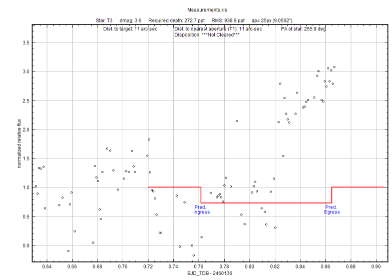
Figure 3: dmagRMS-plot of our target TOI 5944.01



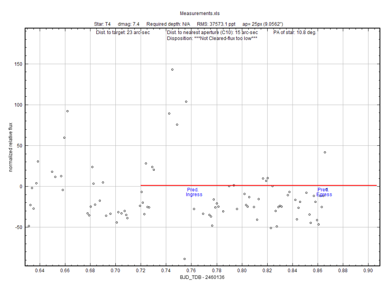
(a) T1



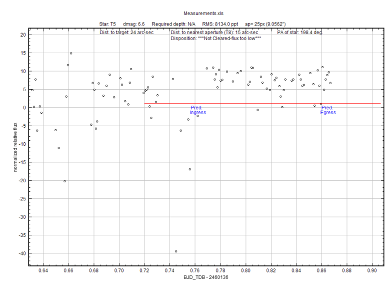
(b) T2



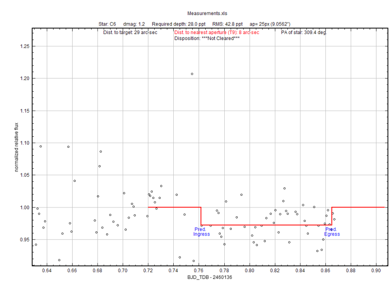
(c) T3



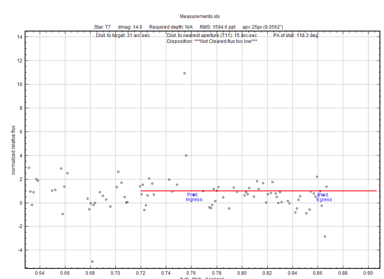
(d) T4



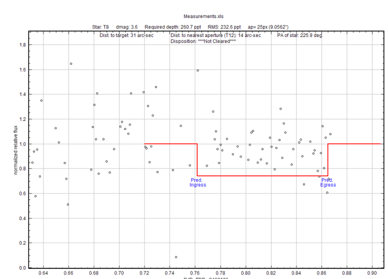
(e) T5



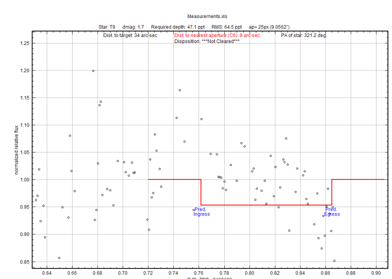
(f) T6



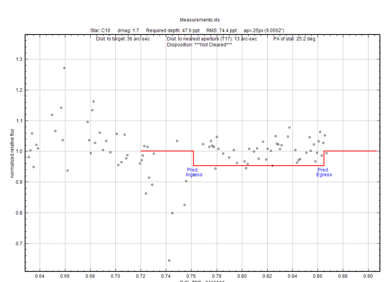
(g) T7



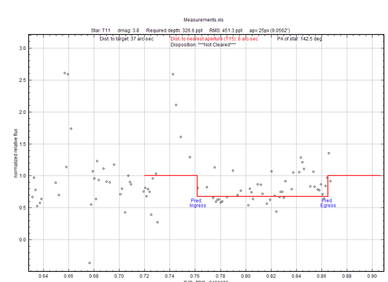
(h) T8



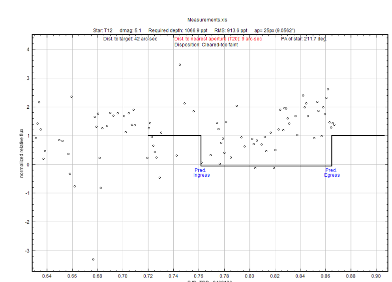
(i) T9



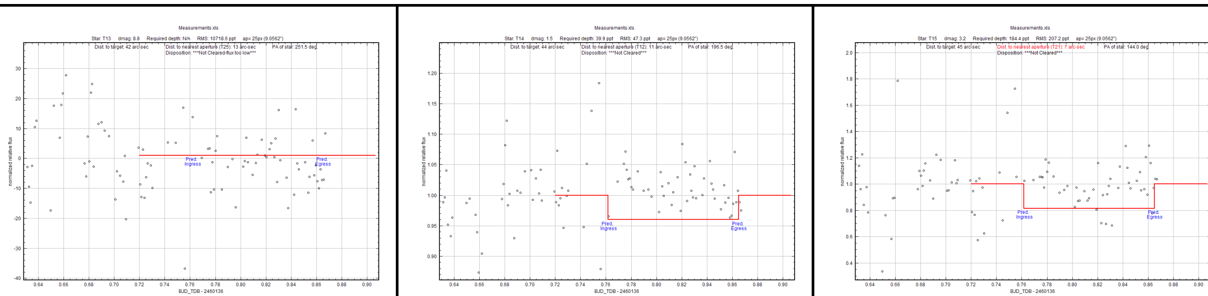
(j) T10



(k) T11



(l) T12



(m) T13 | (n) T14 | (o) T15

Figure 4: Near Eclipsing Binary (NEB) plots for Target Stars (T1 - T15)

4 - Results

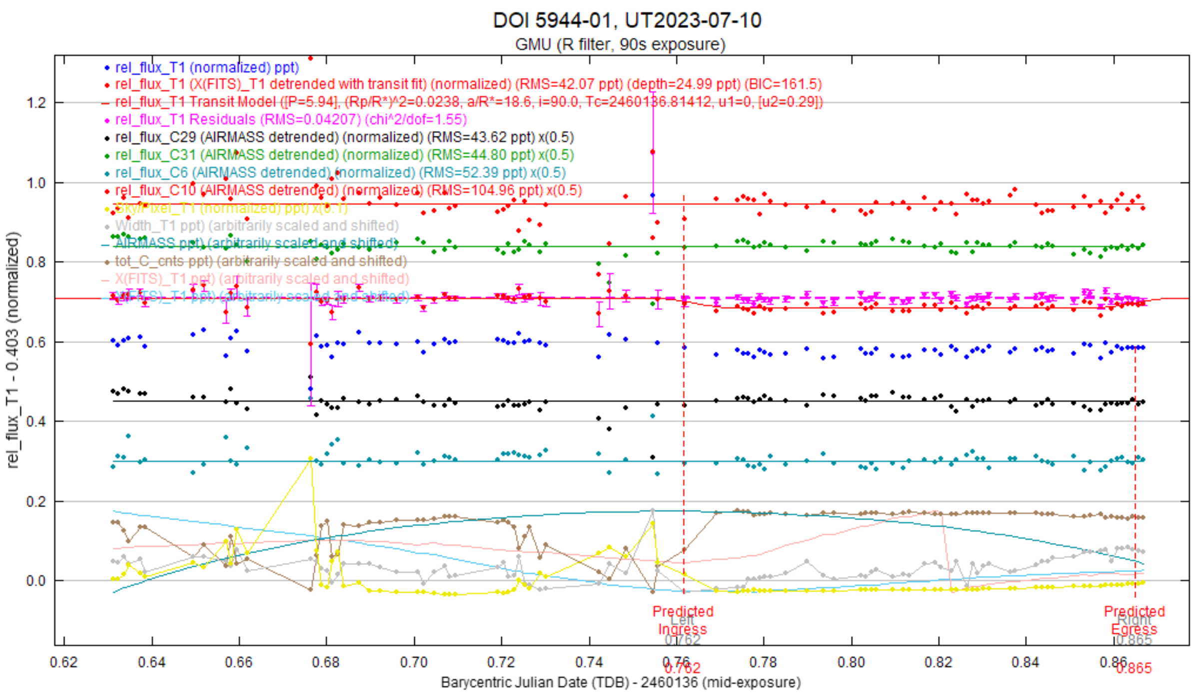


Figure 5: Light curve plot of TESS Object of Interest (TOI) 5933.1 as generated by AstroImageJ

This light curve includes a series of plots that collectively analyze the potential transit of an exoplanet. The first plot shows the normalized flux of T1 over time, offering a baseline of the star's brightness. Variations in flux, particularly a significant drop, could indicate the presence of a transiting exoplanet. The second plot represents the detrended flux, which removes the effects such as air mass and atmospheric transparency, providing a clearer view of any potential transit event. A key plot is the transit model, which simulates what the light curve should look like if a planet is indeed transiting the star. This model is crucial for verifying whether the observed light curve matches the expected pattern of a transit, where the light from the star would temporarily dim as the planet passes in front of it.

The residuals plot displays the differences between empirical observation and the predictions of the transit model. Ideally, the relatively negligible magnitude of these residuals in size indicates the model fits with the observed transit. Large residuals would otherwise indicate that nontrivial changes in the star's brightness or noise from the instruments are affecting the data. Some other plots track the light counts and the stars' positions over time, confirming attribution between changes in brightness to the potential transit and not because of any noncontrollable variables such as changing orbits.

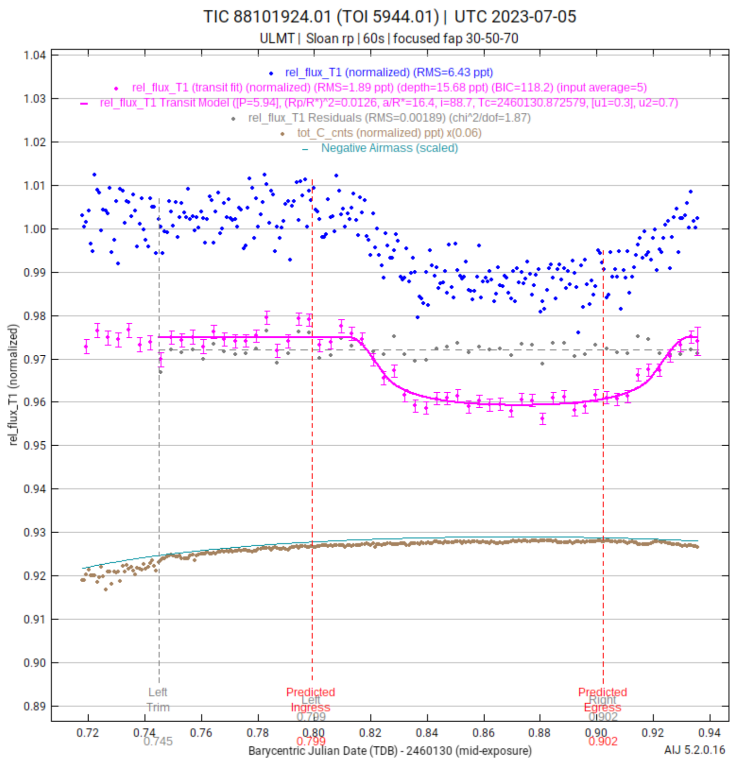


Figure 6: Published light curve plot of TOI 5944.01 on ExoFOP [5]

5 - Discussion

In this section, we will discuss the possible interpretations of our findings. Given the alignment of the exoplanet transit within the ingress and egress times, the possibility of a real transit occurring is significant. However, determining whether or not the dip is significant enough to confirm exoplanet status requires further examination and analysis beyond the scope of this observation. **Figure 4** displays the

Near Eclipsing Binary Plot which attempts to discern potential eclipsing binary stars. TOI 5944.01 could potentially fit in this category but further analysis is necessary to verify the validity of that.

Notably, the light curve plot published on ExoFOP (**Figure 6**) similarly aligns with the relative flux of T1, the possible host star of TOI 5944.01 [5]. The relative alignments in the data between ExoFOP's light curve and the light curve generated by the 90-second science exposures' data collected by the GMU 0.8 telescope reveal a significant possibility of an exoplanet's transit occurring. Further, the time, duration, and depth of the transit signal observed in our follow-up align well with the predicted and measured values provided by the Transiting Exoplanet Survey Satellite (TESS), further supporting our hypothesis's confirmation.

6 - Conclusion & Future Work

Our analysis of TOI 5944.01's light curve involved the processing of 238 images from the GMU telescope, incorporating dark and flat images to correct for distortions. Following data reduction, 194 science exposures were used for all subsequent analyses. Accurate RA and DEC coordinates were assigned through plate solving, enabling multi-aperture photometry, generating the measurement table and the associated data that laid out the functions of the light curve generation step. Ultimately, the transit hypothesis, supported by normalized and detrended flux plots, suggests an exoplanet transiting TOI 5944.01. The close match between the observed light curve and the transit model, along with minimal residuals, indicates a valid transit event. TOI 5944.01 is unlikely to be a false positive. Additional plots confirmed that observed brightness variations are likely due to the transit rather than observational artifacts.

We invite further research to continue the investigation into TOI 5944.01 to confirm its exoplanet status. Given the distinct conspicuousness of the transit across multiple data sets and observations, it is presently impossible to fully confirm TOI 5944.01 as a valid exoplanet. Furthermore, future research should focus on expanding the observational dataset to enhance greater precision in generating the light curve and discerning transits. Finally, future research concerning the specific characteristics and properties of TOI 5944.01 such as its size, density, surface conditions, and more is recommended. These efforts will contribute to a more comprehensive understanding of TOI 5944.01 and advance our knowledge of exoplanetary systems.

References

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