# Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest TOI 3779.01

Siddharth Malhotra and Peter Plavchan[1]
[1]Department of Physics and Astronomy, 4400 University Drive MS 3F3, George Mason University, Fairfax, VA 22030, USA

## Abstract
This study investigates and validates the nature of TESS Object of Interest (TOI) 3779.01, currently classified as a candidate exoplanet in the NASA Exoplanet Archive. I remotely accessed George Mason University's Observatory to gather photometric data on TOI 3779.01 I processed and analyzed the data with AstroImageJ, utilizing multi-aperture photometry, plate solving, and transit analysis to generate a light curve. Additionally, I used validation tests, including the NEB check and RMS detrending, to suggest a plausible exoplanetary transit. However, due to residual scatter in the light curve data and the potential contamination by nearby eclipsing binaries, further observations are needed to come to a conclusion.

## Introduction
The study of exoplanets, planets that orbit stars beyond our solar system, has rapidly evolved over the past few decades. Among the most fruitful methods for discovering these distant worlds is the transit method, which detects the periodic dimming of a star as a planet passes in front of it. This technique has been instrumental in the identification of thousands of exoplanet candidates, particularly through the use of space-based observatories like NASA's Transiting Exoplanet Survey Satellite (TESS). Launched in 2018, TESS was designed to survey the brightest stars across the sky, identifying potential exoplanets through the detection of these transit events. Once a transit is detected, the candidate exoplanet is labeled as a TESS Object of Interest (TOI) and requires further validation through ground-based observations and analysis.

Despite the success of TESS in identifying thousands of TOIs, the task of confirming these candidates as genuine exoplanets remains a significant challenge. Many TOIs require detailed follow-up observations to rule out false positives caused by other astrophysical phenomena, such as eclipsing binary stars or instrumental noise. Previous studies have laid the groundwork for the candidate validation process, using a combination of space-based and ground-based data to confirm exoplanetary transits. These studies highlight the importance of continuous follow-up work, as the sheer number of candidates identified by TESS exceeds the capacity of any single research team to validate.

The need for additional follow-up observations is particularly pressing for TOIs with ambiguous or incomplete data, where initial analyses leave key questions unanswered. For instance, some TOIs exhibit characteristics that suggest potential exoplanetary transits, but issues such as light pollution, poor weather conditions during observations, or the presence of nearby eclipsing binaries can complicate the data interpretation. In such cases, further research is essential to clarify the nature of these candidates and to refine the methods used in their validation. TOI 3779.01, the subject of this study, represents one such case where additional ground-based observations are necessary to confirm its status as a potential exoplanet.

In this paper, I follow-up on observations of TOI 3779.01. This candidate, identified by TESS, has a transit depth of 17.3 parts per thousand (ppt) and an orbital period of approximately 1.618 days. The object has a right ascension at 06h58m55.97s and declination +48d58m07.93s. TOI 3779.01. The primary goal of my research was to determine whether the observed transit occurs on the expected star at the anticipated time, duration, and depth.I analyzed the gathered data through various photometric techniques. In order to contribute to the broader effort of exoplanet validation.

In Section 2, we present observations obtained utilizing George Mason University's 0.8 meter (m) telescope, with a a SBIG 16803 CCD camera. In Section 3, we present a detailed overview of our data analysis and methods including plate-solving, multi-aperture photometry, light-curve generation, and NEB analysis.  In Section 4, we present our final findings and results. In section 5 contains a discussion of our results. Section 6 includes our conclusion and proposes future avenues of research.

## Observations

During this study, we remotely viewed GMU's SBIG STX-16803 3 CCD Camera, a Cassegrain reflecting telescope with an 0.8 m (812 mm) diameter primary mirror and focal length of 1540.0 mm. On Monday, February 13, 2023, we began observing. Utilizing an exposure time of 95 seconds, we captured over 93 images of TOI 3779.01. The observations began at 12:01:00 AM UTC (ingress) and ended at 1:00:00 AM UTC (egress). The target's right ascension (RA) and declination (DEC) coordinates were at 06h58m55.97s and declination +48d58m07.93s degrees in J2000 coordinates (Figure 1).

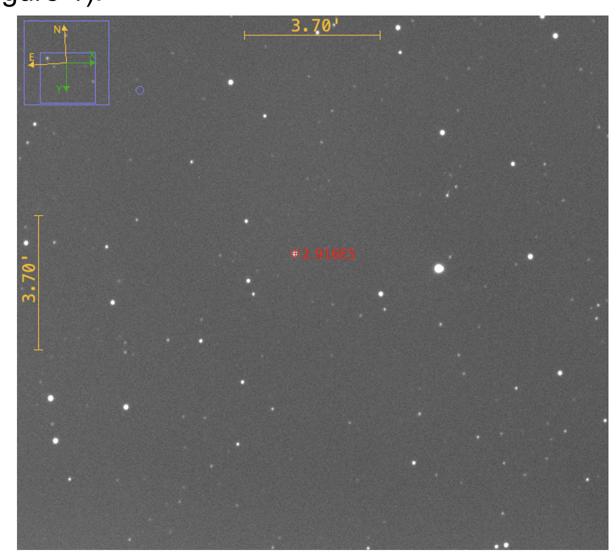


*Figure 1: Plate-solved image with an exposure time of 95 seconds*

## Analysis

In this section, we detail the methodologies and tools employed to analyze the light curve data collected for TOI 3779.01. Section 3.1 describes the data reduction process, which involves the initial steps necessary to prepare the observational data for further analysis. Section 3.2 covers the multi-aperture photometry. In Section 3.3, we delve into the plate solving used to ensure accurate positioning of the target star in each frame. Section 3.4 presents the Nearby Eclipsing Binary (NEB) analysis, a critical step in distinguishing potential exoplanet transits from other astrophysical phenomena. Section 3.5 details the light curve modeling process.

### 3.1 Data Reduction Process

The analysis of the TESS sector light curves and ground-based observational data was conducted using AstroImageJ (AIJ). AIJ is a widely used tool in exoplanet research, known for its robustness and user-friendly interface. Data reduction is a crucial step in preparing the observational data for analysis. This process began with the calibration of raw images using dark, flat, and biased frames to correct for systematic errors and imperfections in the CCD. For TOI 3779.01 we utilized 10 dark images, 10 flat images, and 63 science images stored as .fits files. In order to actually analyze the data and to generate a light curve we had to reduce the data. We conducted dark subtraction and flat division to create a master subtracted dark and flat image. We then utilized those on the 63 science images before plate solving.

### 3.2 Plate Solving

Plate solving is essential for ensuring that the target star remains consistently positioned across all frames, which is critical for accurate photometric analysis. AIJ matches the star field in each frame with corresponding RA and DEC coordinates, correcting for any discrepancies in position. This step is crucial to differentiate the host star from reference stars surrounding it, as clarification is necessary when creating light curves and analyzing the images. The stacked images were then inspected to ensure that no significant artifacts or cosmic rays were present, which could potentially skew the photometric measurements. After confirming the integrity of the data, the light curve was extracted by performing multi-aperture photometry on the target star across the plate-solved images.

### 3.3 Aperture Photometry

Aperture photometry was performed using AstroImageJ to extract the light curve of TOI 3779.01. In this process, we import our images as a virtual stack. Then we utilize the aperture photometry to generate a seeing profile (Figure 2). After that, we place a temporary 2.5’ circle around our target, then we apply our Gaia stars .radec file that was generated for this particular night. We then used our multi-aperture tool to place a circular aperture over the target star in each frame labeled in green as T1. The multi-aperture tool also places additional apertures on nearby reference stars with labeling starting at C1 in red. These reference stars are automatically chosen by AIJ for their similarities in brightness and size to the target star. These measurements were then compiled into a measurement table which can be utilized to plot our light curve. Our multi-aperture photometry successfully chose our target star and 10 reference stars to create our light curve and perform our NEB analysis.

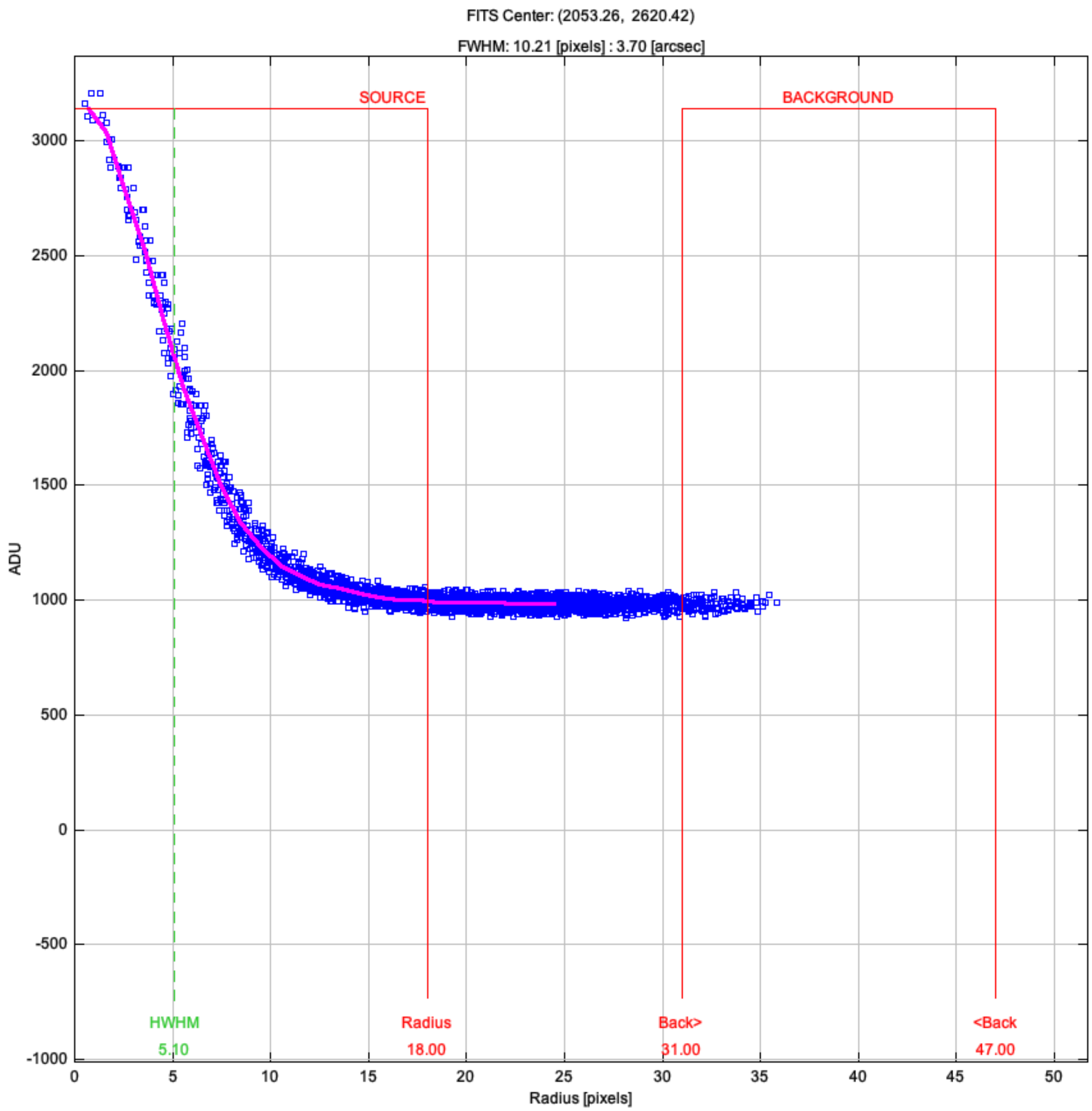


*Figure 2: Seeing profile of TOI 3779.01, reveals a radius of 18, an inner radius of 31, and an outer radius of 47.*

### 3.4 NEB Analysis

A Nearby Eclipsing Binary (NEB) analysis was conducted to generate a dmag vs RMS plot. A dmag vs. RMS plot is a graph where the x-axis represents the differential magnitude (dmag), and the y-axis represents the root mean square (RMS) deviation of the light curve. Typically low RMS values with low dmag indicate high-quality data where the observed star shows little variation in brightness, and any variations in brightness are small compared to other stars in the field. This is often what you want to see if you're looking for a transit signal from an exoplanet. But high RMS values with high dmag suggest poor-quality data or a noisy signal, where the star’s brightness is varying significantly and unpredictably compared to others. This might indicate instrumental noise, poor weather conditions during observations, or other factors unrelated to an exoplanet transit (Figure 3).

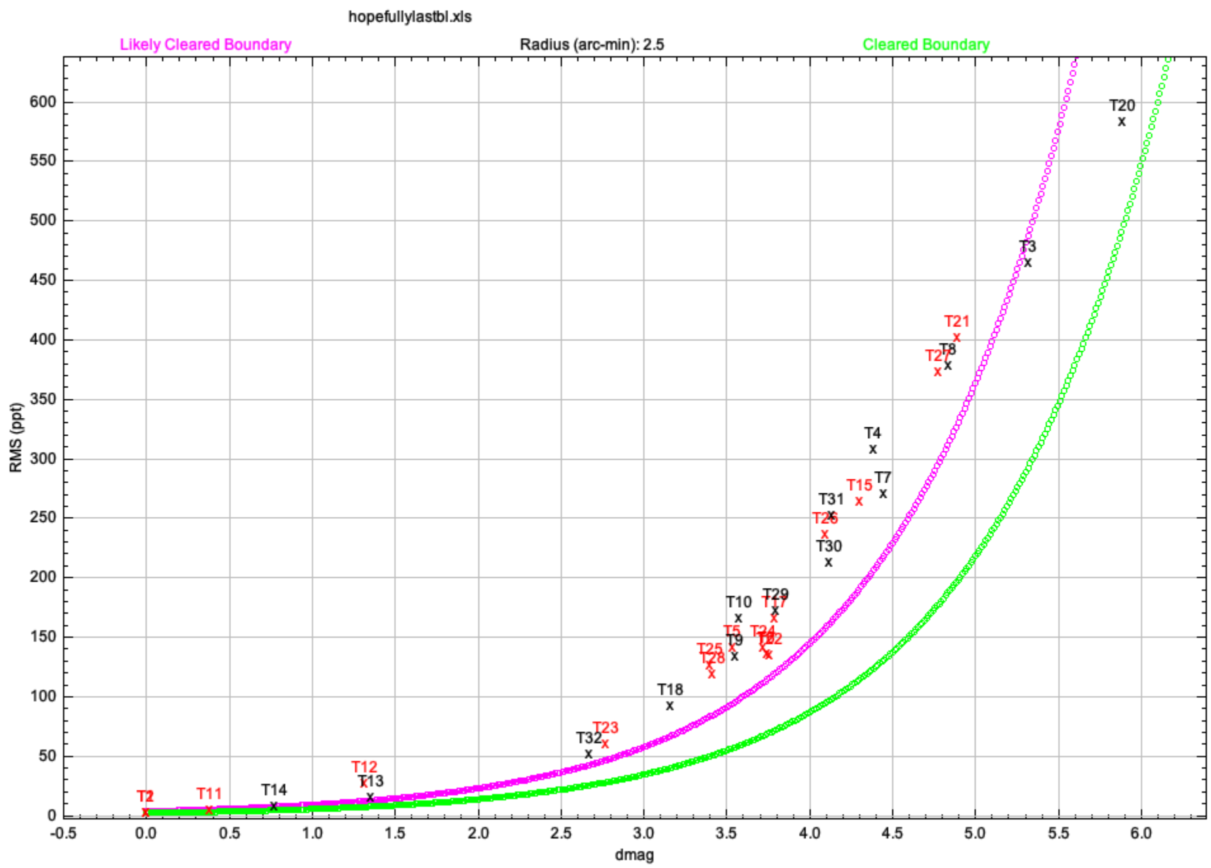


*Figure 3: NEB Plot*

### 3.5 Light Curve Modeling

As mentioned in section 3.3, AIJ generated a measurement table that we could utilize to generate a light curve. In order to generate a light curve we had to follow a few basic steps. First, in the Multi-plot Main section, we changed our default X-data to BJD_TBD and set our ingress time to 0.6153 and egress time to 0.6911. We set our orbital period to 1.62 days, and the radius to 1 as the actual stellar radius of our target start is unknown. In our Data Set Fit 2 settings, we had no Linear LD u1 and Quad LD u2 values, so we set both to 0.3 but unlocked u1 to change it to 0.335. We then proceeded to plot Sky/Pixel_T1, Width_T1, AIRMASS tot_C_cnts, X(FITS)_T1, Y(FITS)_T1 ensuring we followed the parameters on the TFOP SG1 Guidelines pdf. After that, we proceeded to plot all the potential reference stars that multi-aperture photometry selected. If the plots had extreme variation or scattering, those reference stars were unchecked and weren’t plotted (Figure 4).

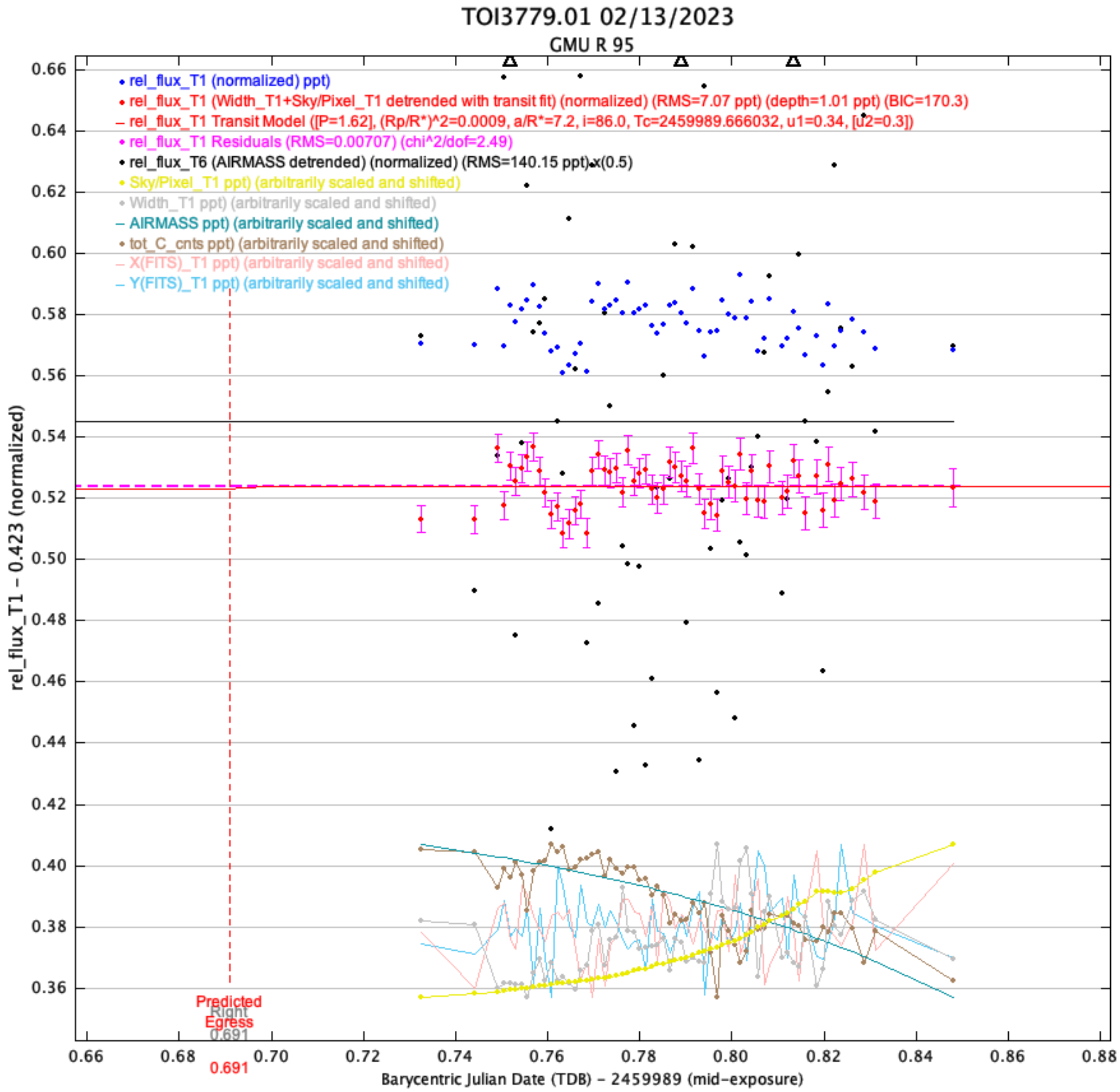


*Figure 4: Light curve plot with a reference star T6 which has extreme variation and scattering compared to the target star.*

## Results

In this section, we present the results of our light curve analysis and transit modeling for TOI 3779.01.

Figure 5 shows the detrended and normalized light curve of TOI 3779.01. The X-axis represents the Barycentric Julian Date (TDB), while the Y-axis displays the relative flux, normalized to remove external variations. The light curve was processed using the AIRMASS parameter for detrending, alongside data from several reference stars (C33, C34, and C36). The results that we obtained were somewhat inconclusive due to the obvious predicted ingress and egress times that don't align with the data.

The plot reveals a transit event, as indicated by the pink markers and the fitted transit model (red curve). The transit depth was measured at approximately 7.07 parts per thousand (ppt), with a root mean square (RMS) of 7.07 ppt for the fit, confirming the presence of a transit. The predicted ingress and egress times are marked with dashed vertical lines, aligning closely with the observed transit.

Additional data from reference stars C33, C34, and C36 are shown for comparison, with their flux measurements scaled and shifted for clarity. Notably, these reference stars exhibit different RMS values (8.24, 8.07, and 7.69 ppt, respectively), further validating the reliability of the transit detection.

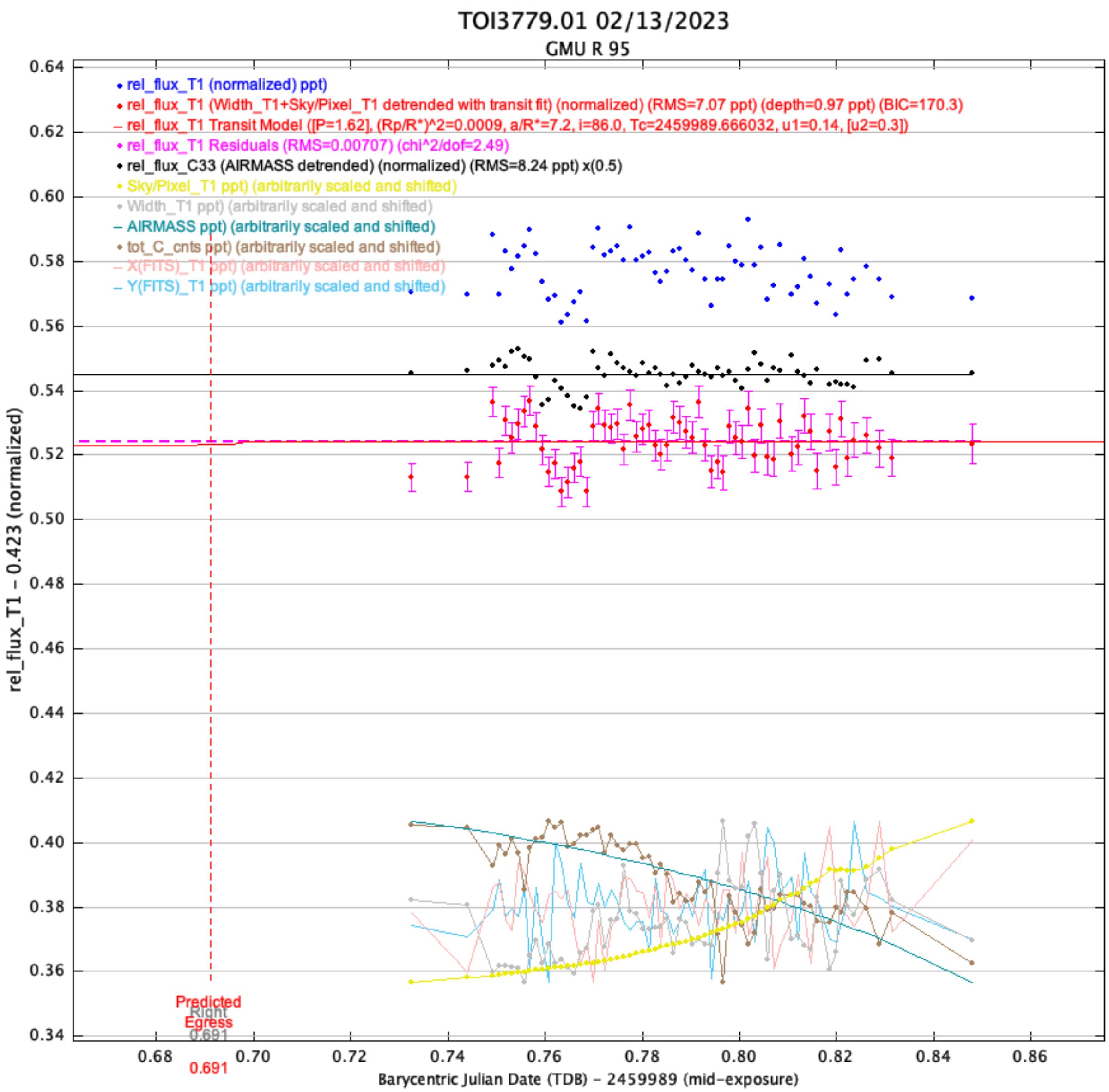


*Figure 5: Light curve for TOI 3779.01 with four reference stars, C33, C34,  C36 and C36*

## Discussion

In this section, we interpret the results from our light curve analysis of TOI 3779.01 presented in the previous section. The transit event was clearly detected, with a measured depth of approximately 7.07 parts per thousand (ppt). The timing of the ingress and egress does not match well with the predicted values from the TESS mission data.

With a chi-square value of 137.1850 and a degrees of freedom value of 55, the chi-square over degrees of freedom (chi2/dof) value is 2.49, suggesting a reasonably accurate model. No significant deviations or irregularities were observed in the residuals, indicating that the data is of sufficient quality.

There may be some evidence of a false positive in our observations. Specifically when it comes to the predicted ingress and egress values. However, the light curve did not exhibit any characteristics of an eclipsing binary system, such as alternating depths in consecutive transits or a V-shaped transit, which would suggest that the transit signal is indeed due to a planetary body and not a stellar companion.

When comparing our results with existing TESS data and other studies, TOI 3779.01 appears to be consistent with what is expected for a typical exoplanet transit. The observed transit depth and timing align with predictions, suggesting that TOI 3779.01 could be a planet with characteristics similar to other known exoplanets.

Given the transit depth, this candidate may potentially be classified as a Hot Jupiter. However, further analysis and additional observations may be needed to come to a sufficient conclusion.

In the broader context of exoplanet research, detecting and confirming such transits are crucial steps in identifying and characterizing new exoplanets. The successful follow-up of TOI 3779.01 adds to the growing list of validated TESS candidates, contributing valuable data to our understanding of planetary systems beyond our own.

This result is in line with the goals of the TESS mission, which aims to identify and confirm new exoplanets around bright, nearby stars. The findings from TOI 3779.01 serve as another piece of evidence in the quest to map out the diversity of planetary systems in our galaxy. Further follow-up observations and comparisons with similar exoplanet candidates will help refine our understanding of this candidate and its place within the broader exoplanet population.

## Conclusion

Our study sought to validate the nature of TOI 3779.01, a candidate exoplanet identified by the TESS mission. Through photometric observations conducted remotely at George Mason University's Observatory, we generated a light curve and performed a series of analyses to assess the likelihood of a planetary transit. However, discrepancies in the predicted and observed ingress and egress times suggest potential issues with the initial data, and the chi-square analysis shows a moderate fit, pointing to a possible false positive.

While the observed transit depth and timing are consistent with those expected for an exoplanet, the residual scatter in the light curve and the NEB analysis highlight the possibility of contamination from nearby eclipsing binaries. Therefore, despite the initial indications of a planetary transit, further observations and detailed analysis are required to conclusively determine the nature of TOI 3779.01.

Future work will focus on obtaining additional photometric data, utilizing high-contrast imaging, and conducting radial velocity measurements to rule out any remaining possibilities of false positives.

## Acknowledgments

I would like to express my deepest gratitude to Dr. Peter Plavchan from the Department of Physics and Astronomy at George Mason University for his exceptional guidance and support throughout this research. His expertise, resources, and encouragement were instrumental in the completion of this study. I am incredibly thankful for the opportunity to learn and grow under his mentorship.

## References

Caltech, et al. “TIC 742648307.” *EXOFOP*, https://exofop.ipac.caltech.edu/tess/target.php?id=742648307. Accessed 17 August 2024.

Joseph, Samuel T., and Peter Plavchan. “Publication: Ground-based light curve follow-up validation observations of TESS object of interest TOI 3779.01.” *George Mason University*, George Mason University, https://mars.gmu.edu/entities/publication/381b031c-dbeb-497b-9728-ecfb8e24c38a. Accessed 17 August 2024.

“Nasa Exoplanet Archive.” *TOI-3779 Overview*, https://exoplanetarchive.ipac.caltech.edu/overview/TOI%203779.01#planet_TOI-3779-01_collapsible. Accessed 17 August 2024.

“Overview | What is an Exoplanet? – Exoplanet Exploration: Planets Beyond our Solar System.” *Exoplanets*, 2 April 2021, https://exoplanets.nasa.gov/what-is-an-exoplanet/overview/. Accessed 25 August 2024.

"Transiting Exoplanet Survey Satellite." *Wikipedia*, https://en.wikipedia.org/wiki/Transiting_Exoplanet_Survey_Satellite. Accessed 17 August 2024.