Ground-based light curve follow-up validation observations of TESS object of interest TOI 4064.01

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Abstract

The TESS satellite scans the sky for possible exoplanets using the transit photometry method. From this initial observation, any possible exoplanet candidates are marked as objects of interest and selected for follow-up ground-based observations. This paper presents the results of follow-up ground-based observation conducted on the candidate exoplanet TOI 4064.01. The goal of this observation was to determine if the transit detected for TOI 4064.01 occurred near the predicted star at the expected time with the predicted duration and orbital depth. This process was accomplished using AstroImageJ to create and analyze the light curve. Observation data of TOI 4064.01 was obtained from the George Mason University 0.8m telescope and was plate-solved using AstroImageJ. After generating a light curve and performing an NEB check, it is inconclusive whether or not there is a transit. This study aims to provide a foundation for any future work that may be conducted on TOI 4064.01.

Introduction

The study of exoplanets is an important subfield within astronomy. Since the first confirmation of an exoplanet detection in 1992 by Aleksander Wolszczan and Dale Frail, astronomers have dedicated decades to the discovery of such bodies (National Aeronautics and Space Administration, 2024). And, in the years since, there have been many advancements both in the discovery of exoplanets and the technology used to analyze them.

One of the most common methods of discovering exoplanets is the transit photometry method, having found nearly 94.2% of all exoplanets in combination with radial velocity (Teledyne Princeton Instruments, 2021). A planet transit occurs when a planet passes between a star and the observer, causing the light levels measured from the star to lower. This effect can be measured using light curves that plot the measured light received from the star over a determined period. These patterns can also reveal several characteristics about an exoplanet. For instance, the amount of light lost can denote the size of a given planet. Today, there are over 5,000 exoplanets discovered or validated to orbit other stars (Clavin, 2022). The Transiting Exoplanet Survey Satellite (TESS) launched in 2018 and monitors millions of stars for temporary drops in brightness caused by planetary transits. Since the TESS mission looks at large sections of the sky all at once, it uses a relatively low-resolution camera (21 arcseconds per pixel), a higher-resolution ground-based verification is necessary to verify that actual exoplanets have been observed (National Aeronautics and Space Administration, 2024).

Although many papers validating certain exoplanets exist, such as TOI 1221-b (a warm sub-Neptune) and TOI 181b (a sub-Saturn), there still remain many more objects that have yet to be analyzed (Mann et al., 2023). In this paper, we take the opportunity to perform said ground-based observations on TOI 4064.01 and fill in gaps within the data. The goal of these observations is to determine whether the transit of the objects occurs on the expected star, at the expected time, with the expected duration and depth. There are a few known basic characteristics about TOI 4064.01, including its radius of 9.9556 Earth radii, an orbital period of 3.88500 days, and a transit duration of 2.619787 hours. This information is a key component of our analysis of TOI 4064.01.

This paper will cover our observation and analysis of TOI 4064.01. In Section 2, we present our observations from TESS and the George Mason University 0.8m telescope. In Section 3, we present our analysis of the TESS light curve for TOI 4064.01 and our ground-based light curve analysis. In Section 4, we present our light curve results. In Section 5, we discuss the results obtained from this analysis. In Section 6, we present our conclusions and future work for the candidate.

Observations

In Section 2.1, we present the TESS Object of Interest 4064.01 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 curves. In Section 2.3, we present a summary of the observational data for TOI 4064.01 collected by George Mason University's 0.8m telescope.

TESS Observational Data - 2.1

The TESS Input Catalog ID of our object of interest TOI 4064.01 is TIC 219489550. The right ascension (RA) and declination (DEC) coordinates of TOI 4064.01 are 16h13m28.89s and +42d53m07.81s, respectively (MAST Archive).

As measured by TESS, the candidate's transit midpoint is approximately 2459721.688 BJD, the orbital period is 3.88500 days, and the transit duration is 2.619787 hours. Further, the candidate exoplanet's transit depth is approximately 3446.4938862 ppm (parts per million), its radius is about 9.9556 Earth radii, its insulation is 1087.67418539545 Earth flux, and its equilibrium temperature is around 1464.68574515037 K.

TESS also reports that the stellar distance is 756.022 pc, the stellar effective temperature is 5622.4 K, the stellar log(g) is 3.98 cm/s^2, and the stellar radius is approximately 1.6867 Sun radii.

TESS light curves - 2.2

Tess also generated a light curve of TOI 4064.01. Figure 1 presents the relative flux vs. phase plot of the target. There was a slight drop between the hours of -1.3 to 1.3, suggesting its existence in the system and a short period of its transit. Solely judging from the light curve, there was a high likelihood that the target was a true positive, but a follow-up observation such as our study was necessary to confirm the target's identity.

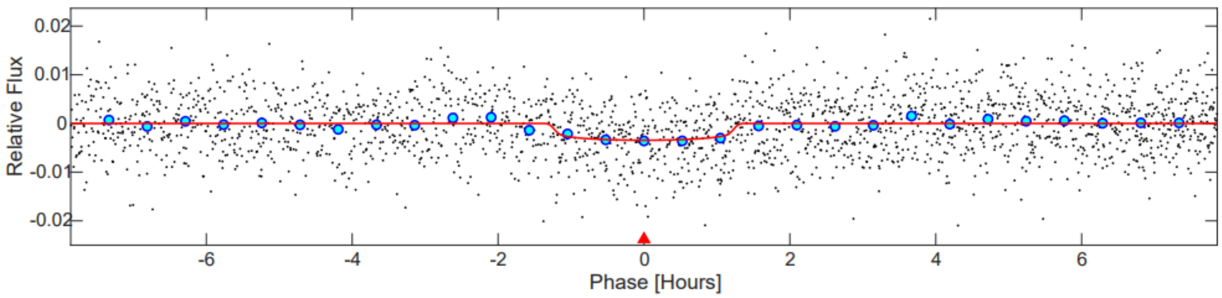

Figure 1. Light curve plot of TOI 4064.01 from the TESS Data Validation report. *Note*. The image was imported from the MAST (Mikulski Archive for Space Telescopes) portal.

GMU Telescope Observations - 2.3

In this study, we used the George Mason University 0.8m telescope in Fairfax Virginia, with a geographic location of -77:18:19.24 longitude, +38:49:41.5 latitudes, and an altitude of 148.72.

We captured a total of 251 Science exposures, each with an 80s exposure time, starting at 21:25 on May 17 and ending at 4:45 on May 18, 2023. The telescope used an R filter. The RA and Dec coordinates of TOI 4064.01 are 16h13m28.89s and +42d53m07.81s, respectively, as referenced in section 2.1.

Analysis

In Section 3.1, we present the tools used to analyze TOI 4064.01 using AstroImageJ, Astrometry.net, and Alnitak. In Section 3.2, we present our process of generating a light curve for TOI 4064.01 on AstroImageJ.

Analysis Tools - 3.1

AstroImageJ is a software used by astronomers to display images captured from telescopes. More prominently, AstroImageJ facilitated data reduction, multi-aperture photometry, and light curve generation. This software also utilized ansvr, a local Astrometry.net plate solver for Windows, for plate-solving the sciences. Due to constant errors with plate-solving a couple of science images, an alternate tool Alnitak was used to plate-solve the failed images. The code uses the plate solver API by nova.astrometry.net. In this study, we use these tools to analyze the candidate exoplanet.

Analysis Using AstroImageJ - 3.1

We used AstroImageJ to generate a light curve of our target, TOI 4064.01.

First, we downloaded and organized the 251 images captured by the GMU telescope on May 17th, 2023, separating the flat darks, science darks, flats, and sciences. This process prepared us for data reduction of the sciences. Afterward, we went through the entire set and removed all suboptimal images, such as those with streaks and shifting. The telescope focused on our object of interest TOI 4064.01, which has RA and Dec coordinates of 16h13m28.89s and +42d53m07.81s.

Then, we performed data reduction of the sciences using the flat, science dark, and flat dark images. Data reduction is necessary as it gets rid of spurious and/or artificial counts caused by various external sources, saving space, improving efficiency, and making it significantly easier to interpret the images.

Next, we plate-solve the sciences. Plate-solving an image assigns each object in an image with RA and DEC coordinates. In doing so, we do not need to align the sciences before doing light curve analysis, cutting down the number of new files being created and saving more memory space in the long run. We plate-solved the first 238 images using the built-in tool in

AstroImageJ, but the last 9 images failed. As a result, we used the Alnitak tool to plate-solve the remaining images. In the end, all plate-solves were successful.

Finally, we generated a measurement table for TOI 4064.01. The table contains the changing fluxes of our target star, the Gaia stars, and the reference stars with time. In order to create this table, we first measure the aperture and annuli radius of TOI 4064.01. We found a radius of 27, an inner annulus radius of 47, and an outer annulus radius of 70 pixels (Figure 2). We then perform multi-aperture photometry with 25 Gaia stars as reference. We also chose 15 additional stars with a similar brightness and size as TOI 4064.01. See Figure 3 for the first science labeled with the reference stars. After multi-aperture optometry, a measurement table is created. We use this measurement table to plot our light curve for TOI 4620.01.

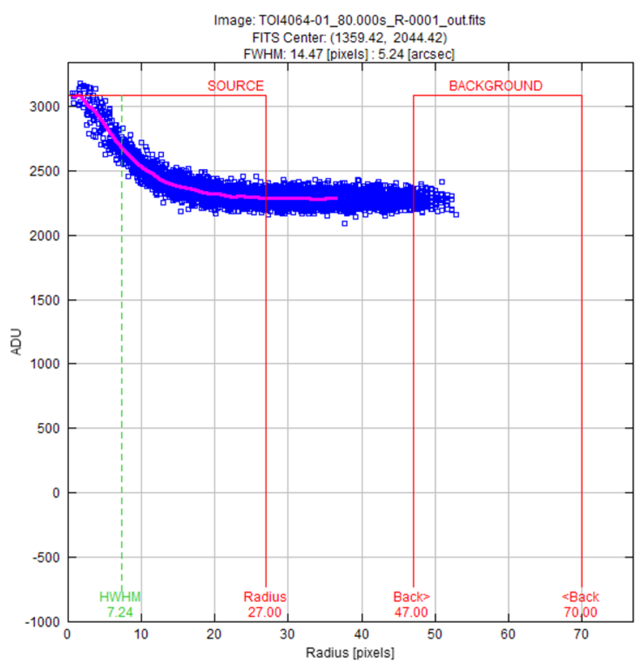

Figure 2. Seeing profile of TOI 4064.01 on AstroImageJ. *Note.* the photometry radius, inner annulus radius, and outer annulus radius of 27.00, 47.00, and 70.00 pixels respectively.

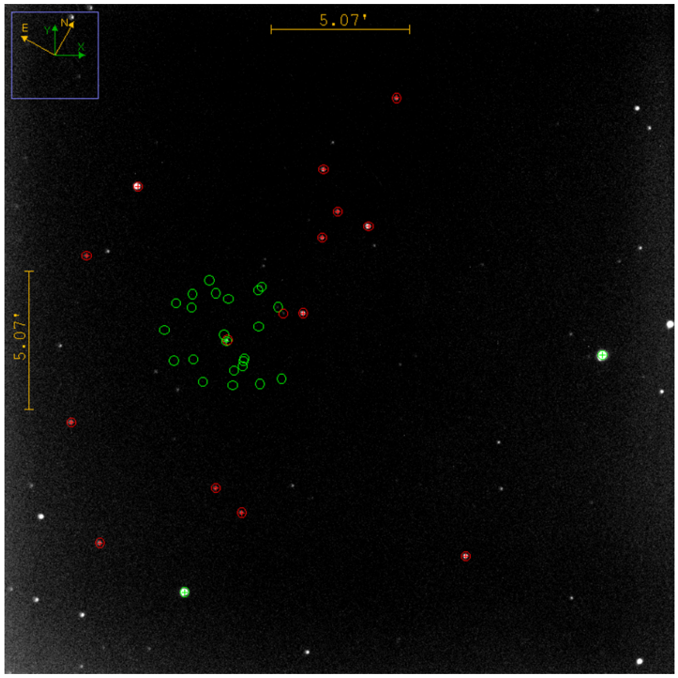

Figure 3. AstroImageJ aperture displaying TOI 4064.01 and all reference stars.

Now, we can use AstroImageJ to plot the light curve for TOI 4064.01. We first input data collected by TESS, including our target exoplanet's period and host star radius. To find the values for Linear LD u1 and Quad LD u2, we use EXOFAST's Quadratic Limb Darkening, inputting R filter, the metallicity, effective temperature, and log(g) (0, 5622.4, and 3.98, respectively). This produced Linear LD u1 and Quad LD u2 of 0.38759033 and 0.26878697. The BJD_{TDB} start and end times for 4064.01 are 10082.7287 and 10082.8075. We can determine the ingress and egress times by looking at the digits after the decimal points, which are 0.7287 and 0.8075, respectively.

We can then configure the light curve by, appropriating the title and selecting all the relevant plots. Then, we reviewed each reference star and deleted the ones with significant variation / scattering. Next, we performed an NEB analysis. We began by checking the dmagRMS-plot for any outliers (Figure 4). NEB stands for near eclipsing binary, and this check is necessary for identifying any potential eclipsing binary stars. TOI 4074.01 could be an eclipsing binary, but further analysis is needed to either confirm or deny this hypothesis. See Figure 5 for NEB Plots corresponding to TOI 4074.01 and all the Gaia stars.

Finally, we can plot the light curve for TOI 4063.01, looking for any noticeable dips in the light curve indicating an exoplanet transit.

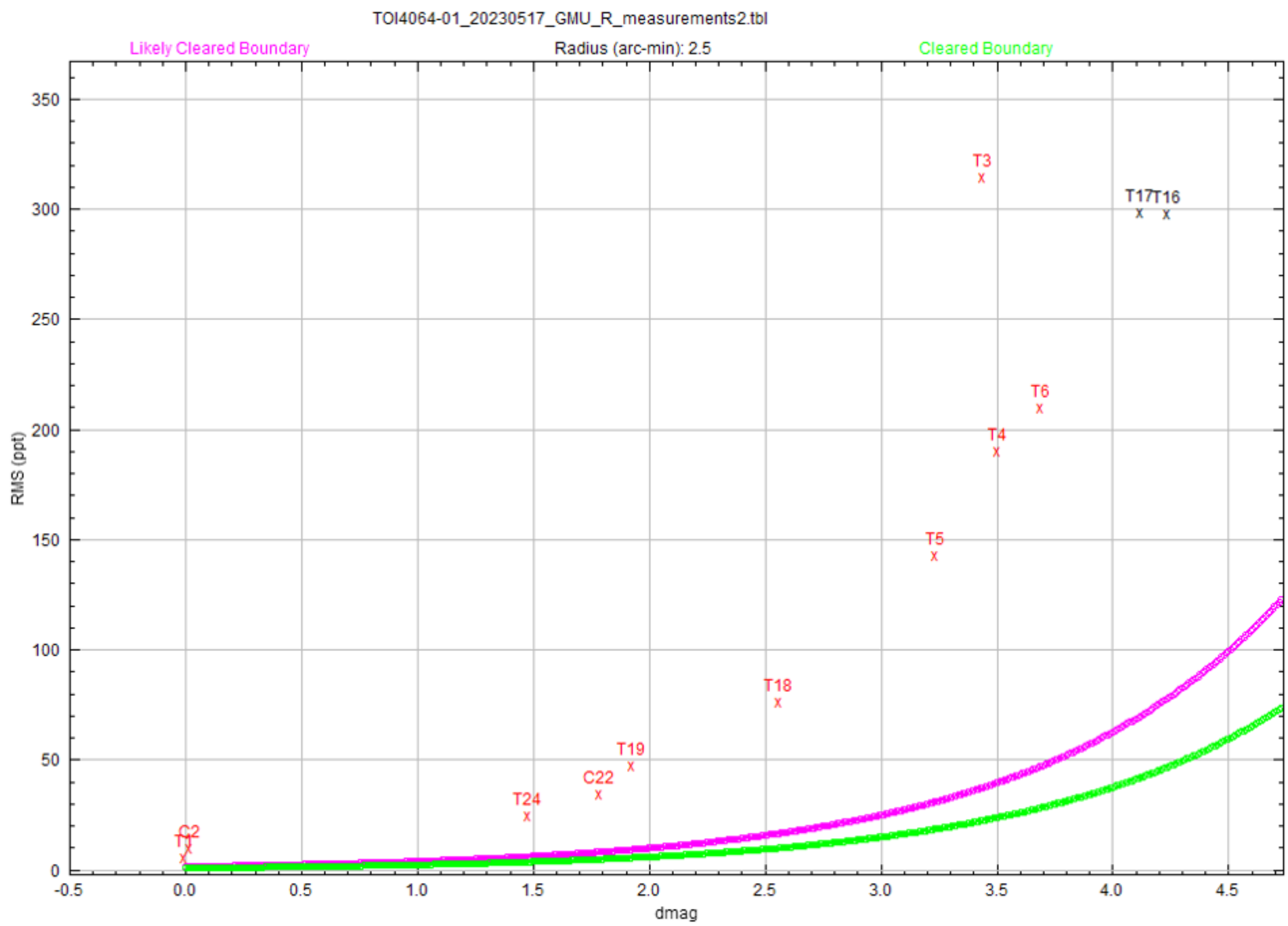

Figure 4. dmagRMS-plot of TOI 4064.01 (T1) and Gaia stars

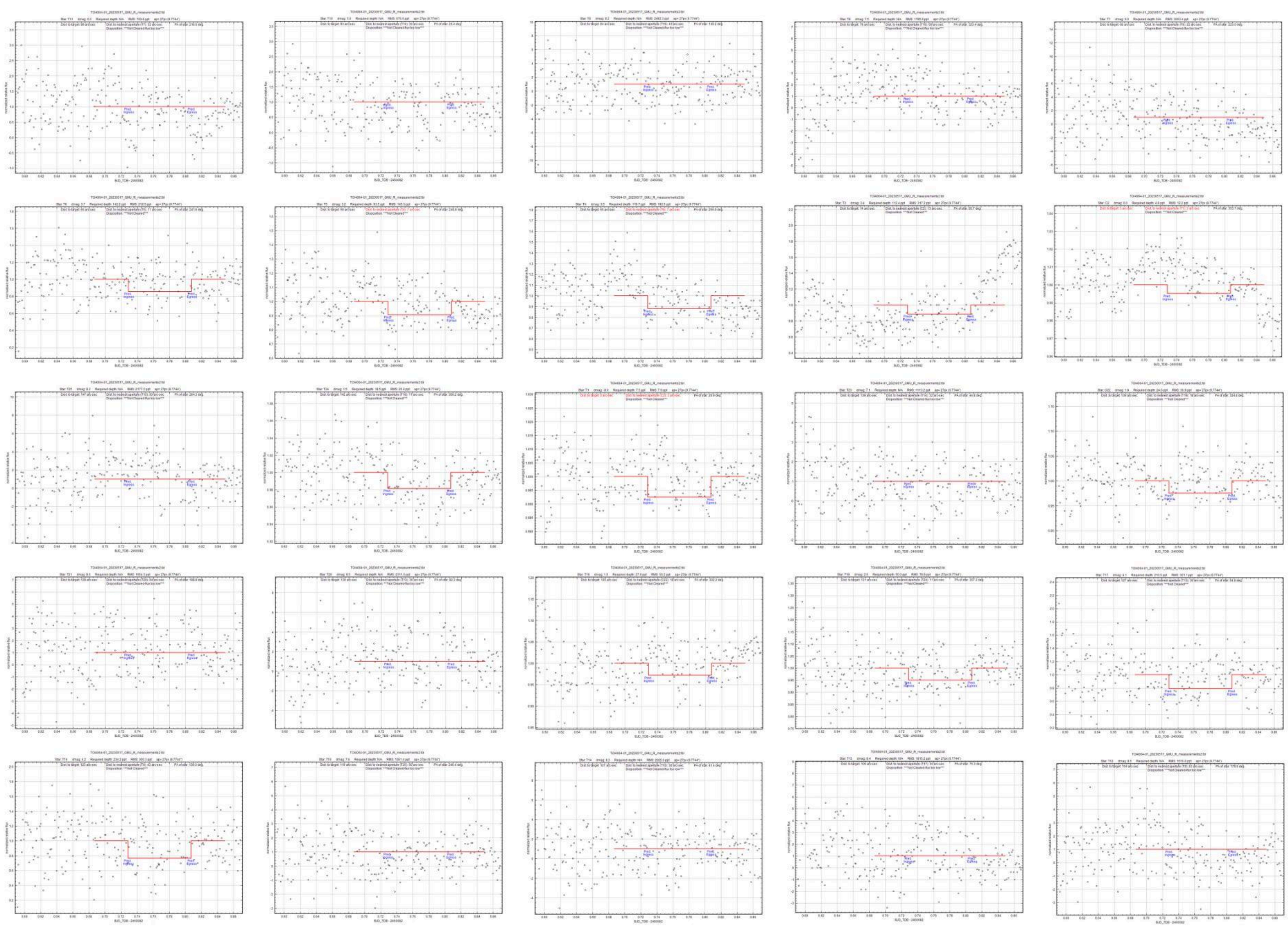

Figure 5. Individual Near Eclipsing Binary (NEB) plots.

Results

Refer to Figure 6 for the light curve of TOI 4064.01 with ingress and egress times of 0.7287 and 0.8075 relative BJD, respectively.

This light curve (Figure 6) incorporates several plots. The first (blue) plots the normalized flux of T1 (TOI 4064.01) in comparison with the reference stars over the captured time. The second plots the relative flux of T1 detrended with WIDTH, Y(FITS), tot_C_cnts, and BJD_TDB, which were necessary to get closer to the predicted depth. The third plots the transit model of TOI 4064.01, which depicts the degree to which the light curve fits a transit. The fourth plots residuals using the chi^2 fit test. The fifth and sixth lines plot the normalized flux of two reference stars C27 and C29. The seventh plots the normalized flux for light in the sky over time. The eight plots the width of T1 over time. The ninth plots the AIRMASS detrending over time, depicting the amount of atmospheric thickness the light travels through. The tenth plots tot_C_cnts (the sum of all the counts for every star). The eleventh plots the X(FITS) (the x-coordinate of T1 over time. And, the twelfth plots the Y(FITS) (the y-coordinate of T1 over time). The ingress and egress times match to a slight dip in the light curve, indicating the existence of a potential exoplanet.

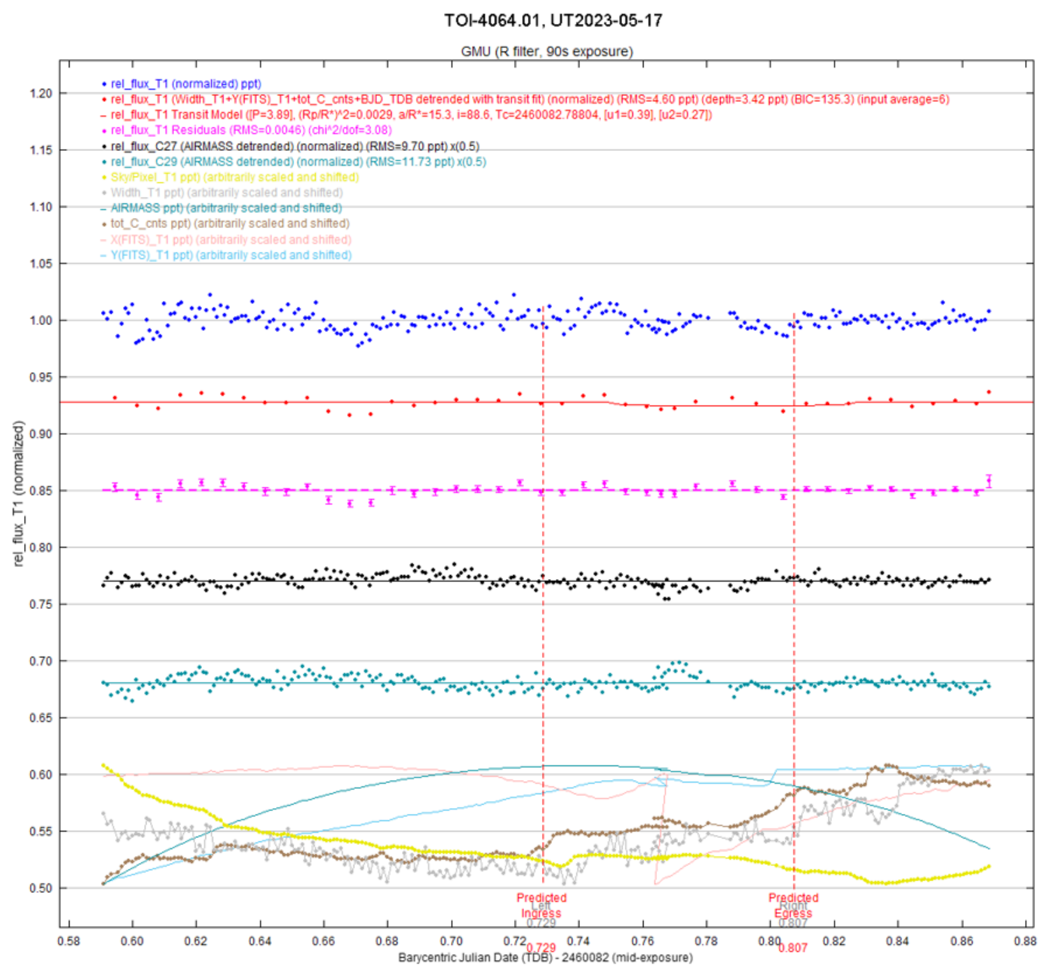

Figure 6. Light curve of TOI 4064.01 from AstroImageJ.

Discussion

In this section, we interpret our findings. Specifically, we determine whether our results indicate TOI 4074.01 is a valid exoplanet.

In short, the ground-based light curve does not show a clear transit detection. Between the predicted ingress and egress, there's a lack of a characteristic dip with the appropriate depth. Due to the lack of transit, we were unable to conduct further analyses using software like ExoFAST, which requires a visible transit on the light curve. This may have been a result of suboptimal data captured as a result of environmental noise / poor conditions (such as cloud coverage, weather, streaking, and more).

The results about the planetary nature of TOI 4064.01 were inclusive and the candidate did not clear the NEB analysis. Overall, this candidate is still open to further analysis by interested parties. This conclusion has left many questions unanswered, and in order to determine if a transit exists, more observations may need to be done on TOI 4064.01. Even if a transit with an appropriate depth appears, an NEB search will need to be done to fully validate the candidate.

Conclusion and Future Work

From our results and discussion, we determined that further observations are required for TOI 4064.01. Namely, a detailed statistical false-positive validation is necessary to rule out the possibility of a false positive. As mentioned earlier, it is also possible that our exposures were far too noisy for an accurate representation of the candidate. Hence, more observations of the target may be useful for the validation of the target. Finally, teams may also be interested in pursuing other methods of detection, such as radial velocity measurements, wherein we measure periodic shifts in the star's spectral lines in order to discover more characteristics of the candidate (minimum mass and shape/size of orbit).

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