Ground-based light curve follow-up validation observations of TESS Object of Interest TOI-5147.01

Nishanth Karanam[1] and Peter Plavchan[2]
[1] Mira Loma High School, 4000 Edison Avenue, Sacramento, CA 95821, USA
[2] Department of Physics and Astronomy, 4400 University Drive MS 3F3, George Mason University, VA 22030, USA

Abstract

Using the on-campus telescope at George Mason University, new images of Tess Object of Interest (TOI) 5147-.01 were taken since those used in the previous follow-up done on this object, so additional analysis was obligatory. These sciences were reduced (eliminating all adverse effects created by the telescope and dark current) and plate-solved (comparing the stars in the sky to the rest of the celestial sphere to identify its celestial coordinates), and multi-aperture photometry performed on them to create a table of measurements by comparing the flux of the target star to the its neighboring stars, making sure that any perceived transit detected was actually a real dip in the light of the target star. A model was fitted to the light curve produced by that table after analysis and detrending, and its best fit parameters were compared to TESS' calculations to eliminate the possibility of this detection being a false-positive and confirm this system as a transiting exoplanet. These results are mixed, and don't imply that this transit is real, but have enough promise that future research into this system is recommended since the transit depth was within the margin of error, the RMS was comparable in ppt (parts per thousand0 to the depth, and the chi-square test implies statistical significance. The egress also lines up with the end of transit. However, the ingress time was at a time that was outside of the error, and none of the nearby stars nor the target were cleared as Nearby Eclipsing Binaries.

1. Introduction

Exoplanets can prove vital to our understanding of planetary systems and formation due to the incredible variety of systems that could exist. As exoplanets pass in front of their host star, they could produce dips in the light received from the star, many candidates of which have been detected by the TESS (Transiting Exoplanets Survey Satellite) Mission. This study aims to validate a TESS candidate as a transiting exoplanet, which is necessary considering the thousand potential candidates. Davoudi et al.[1] performed ground-based light curve analysis of many exoplanets in the Hungarian-made Automated Telescope Network, one of which was HAT-P-22, a host star with characteristics reminiscent of TOI-5147. A paper by Xiao et al.[2] performed a follow-up for this candidate before, but new images were taken more recently, so redoing the analysis would be valuable. TESS' measurements [3] in the NASA Exoplanet Archive calculate that TOI-5417.01 has radius of 7.07511 Earth radii, or 0.6312001 Jupiter radii, with an orbital period of 3.9178573 days. Its host star has an effective surface temperature of 5174.39 Kelvin (K), a mass of 0.877 stellar masses, and 0.877 stellar radii, properties which resemble the Sun. The goal of this study is to be able to confirm TOI-5147.01 as a transiting exoplanet with a 99% accuracy, or it has less than a 1% chance of being a false positive. One aspect of this effort is confirming that the calculated transit depth, duration, and midpoint align with the values calculated for the analyzed light curve. In the next section, we will be looking at the observations of the candidate done by both TESS and the GMU telescope, going into the process of analysis of this data in section 3. Section 4 will evaluate the results of the analysis, and section 5 will be the discussion of those results. Section 6 is the conclusion and future work for these results.

2. Observations

Section 2.1 will list relevant exoplanet and host star properties of the TOI-5147 system, from the TESS Input Catalog [3], NASA Exoplanet Archive, and the Exoplanet Follow-up Observing Program (ExoFOP), among others. Section 2.2 will focus on how the data was collected by summarizing the observational data.

2.1 TESS Data

The TESS Input Catalog ID of TOI-5147.01 is TIC 95361530, and also has entries in the Gaia Archive, the Sloan Digital Sky Survey (SDSS) Catalog, the Wide-field Infrared Survey Explorer (WISE) Catalog, the Two Micron All Sky Survey (2MASS) Catalog, the AAVSO Photometric All-Sky Survey (APASS) Catalog, and USNO CCD Astrograph Catalog (UCAC4)[4]. It's RA and declination are 10h 16m 57.85s and 18d 12m 49.90s, respectively.

TESS' measurements [3] indicate that TOI-5417.01 has a transit depth of 0.427% and a transit duration of 0.739 hours. The transit midpoint in Barycentric Julian Date (BJD) is 2459631.96789.

2.2 GMU Observational Data

For this study, we used the SBIG STX-16803 3 CCD Camera, a 0.8 meter long Cassegrain reflecting telescope at George Mason University (GMU). The telescopes longitude and latitude are -77:18:19.24° and +38:49:41.5°, respectively, at an altitude of 148.72 meters.

296 Science exposures in the R filter were taken with an exposure time of 80 seconds from UTC 00:41:05.44 – 08:49:50.94 on the 20th of February, 2024. Due to streaking from small movements of the camera and glare/a passing satellite, 33 images were discarded.

The flats and flat darks had an exposure of 3.5 seconds. 10 of each were taken, along with 10 science darks.

3. Analysis

Section 3.1 will outline the tools we used to analyze the images of TOI-5147.01, while Section 3.2 will detail the process of data reduction. Section 3.3 will cover how the analysis was performed.

3.1 Analysis Tools

While all images were collected by the GMU telescope, tools are needed to carry out the analysis. AstroImageJ (AIJ)[5] is a program which allows astronomer to view .fits files, reduce data, plate-solve images, generate light curves, among other capabilities.

Another tool used for analysis is the plate-solving catalysts, ansvr, which is the local version of the service provided by astrometry.net.

3.2 AstroImageJ

Sciences are the images of the target itself which are used for data analysis. But there are many factors that could contribute to them being unusable in their current state; see Figure 1. Dark files aim to eliminate all incorrect pixel counts coming from dark current, and flats are taken to eliminate noise, effects from the atmosphere, dust on

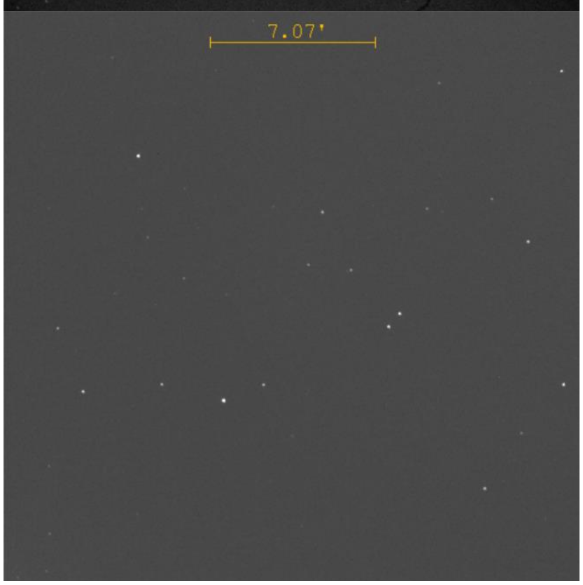

Figure 1*. A sample raw science, number 136. Taken at UTC 04:33:58.51 on February 20th, 2024.* ***Figure 2.*** *The same science that has been reduced and plate-solved.*

the detector, variations in pixels, and so on. Two sets of darks are taken; one with an exposure time equal to the flats, the other with exposure times of the sciences. The first set measures dark current of the atmosphere, and the second measures dark current of the region of sky where the target is located. AIJ's Data Processor (DP) allows for the creation of master dark and flat files, which median combines each pixel from the 10 flats/darks to eliminate all of these effects

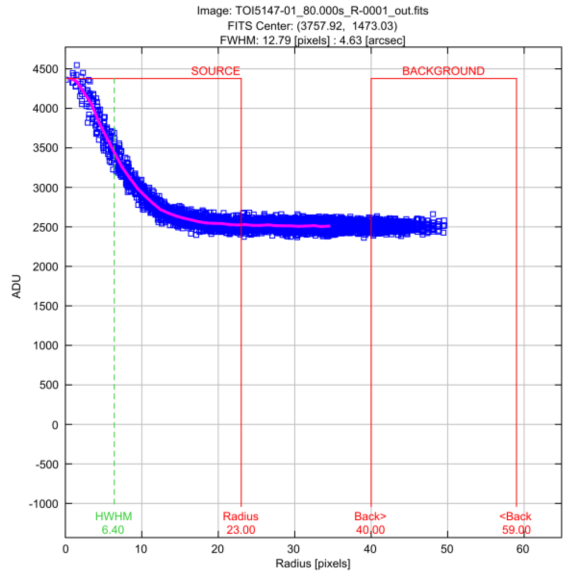

Figure 3. *The seeing profile for the target star.*

from the sciences; this is the process of reducing sciences.

After they are reduced, they need to be plate-solved, which is the process of comparing the pattern of stars to the rest of the celestial sphere to identify which part of the sky the image represents. This is where ansvr is needed, and this is done in the DP window. See Figure 2 to see the results of these processes.

At this point, multi-aperture photometry is necessary. This is where the intensity of target star is compared to other stars in the image while removing all right from the sky to ensure that any dip in the light curve is experienced only by that star and not due to any other extraneous, unrelated influence. The multi-aperture photometry process begins with obtaining a seeing profile (see Figure 3), which graphs the light of the star within a specified radius as distance from the center increases. This profile has predicted values about what the radius of the star is and uses the background to cancel out its light. A temporary radius of 2.5' is placed around the target star, and the *Gaia* .radec file is dragged into the image sequence, which uses any stars in that 2.5' area as a basis for a Nearby Eclipsing Binary (NEB)

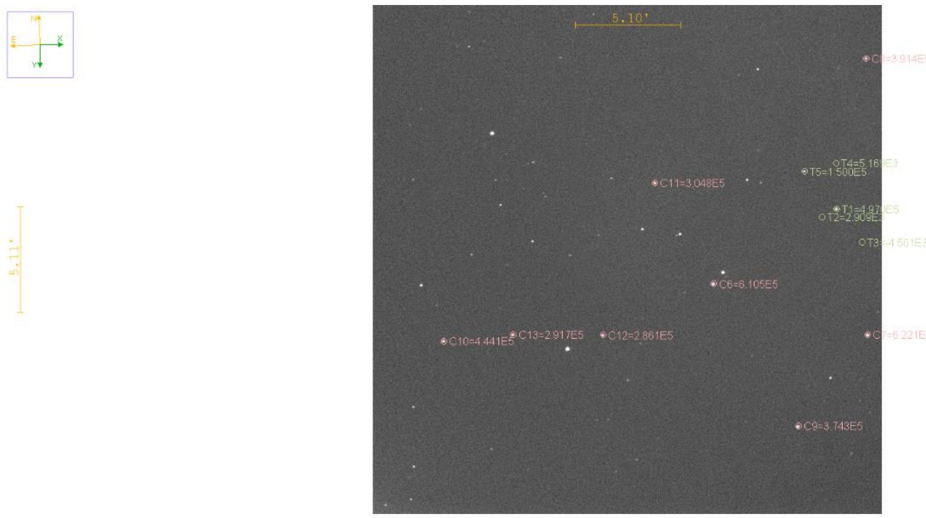

Figure 4. *The apertures used for multi-aperture photometry. All the green marked stars have a label beginning with T; these are stars identified with the* Gaia *.radec file and will be used for the NEB check. The red marked stars are used to produce the measurements table and light curve; these have titles starting with C.*

check. Then all apertures are chosen to have these same predicted values, and after choosing the target, we allow AIJ to choose the rest of the reference stars. Multi-aperture photometry is then started. Once finished, it creates a measurements table, which is used to create the light curve.

To create the light curve, many other parameters are needed besides the measurement table. Along with all the data provided by TESS [3], two parameters, Linear LD u1 and Quad LD u2, are used to fit the model, which are calculated based on filter band, effective surface temperature, metallicity, and surface gravity parameters of the host star. Our Linear LD u1 value is 0.50899030, and the Quad LD u2 is 0.19618982. Predicted ingress and egress times calculated by TESS are plotted as vertical dotted lines to see if the measured light curve lines up. Due to the ingress and egress values being in BJD, they need to be adjusted to the scale of the x-axis. They are calculated by rounding down the ingress time to the nearest integer, and then subtracting this number from both the ingress and egress values. In this study, they came out to be 0.705 and 0.736.

One last process that needs to be done to ensure that the transit isn't a false positive is an NEB check, which can only be done if the .radec file has been overlain during multi-aperture photometry. Once the previous steps were completed, "create NEB plot and report" is performed, which produces plots for each star used in the NEB check, as well as a differential magnitude (dmag) vs. root mean square (RMS) plot; the placement of stars on the graph compared to the boundaries provide insights into whether or not they can be classified as NEBs.

3.3 Analysis

We can now begin the actual analysis. The first thing to do is to open the measurements table obtained earlier along with the associated plot configuration file. Once the plot is opened through the config file, under Multi-Plot Main, the x-axis is changed to BJD_TDB. V.Marker 1 and V.Marker 2 are where the calculated ingress and egress times are inputted. Per standard guidelines, the title includes the target name and date of observations, while subtitle has the university where the observations were made, filter band, and exposure time. In x-

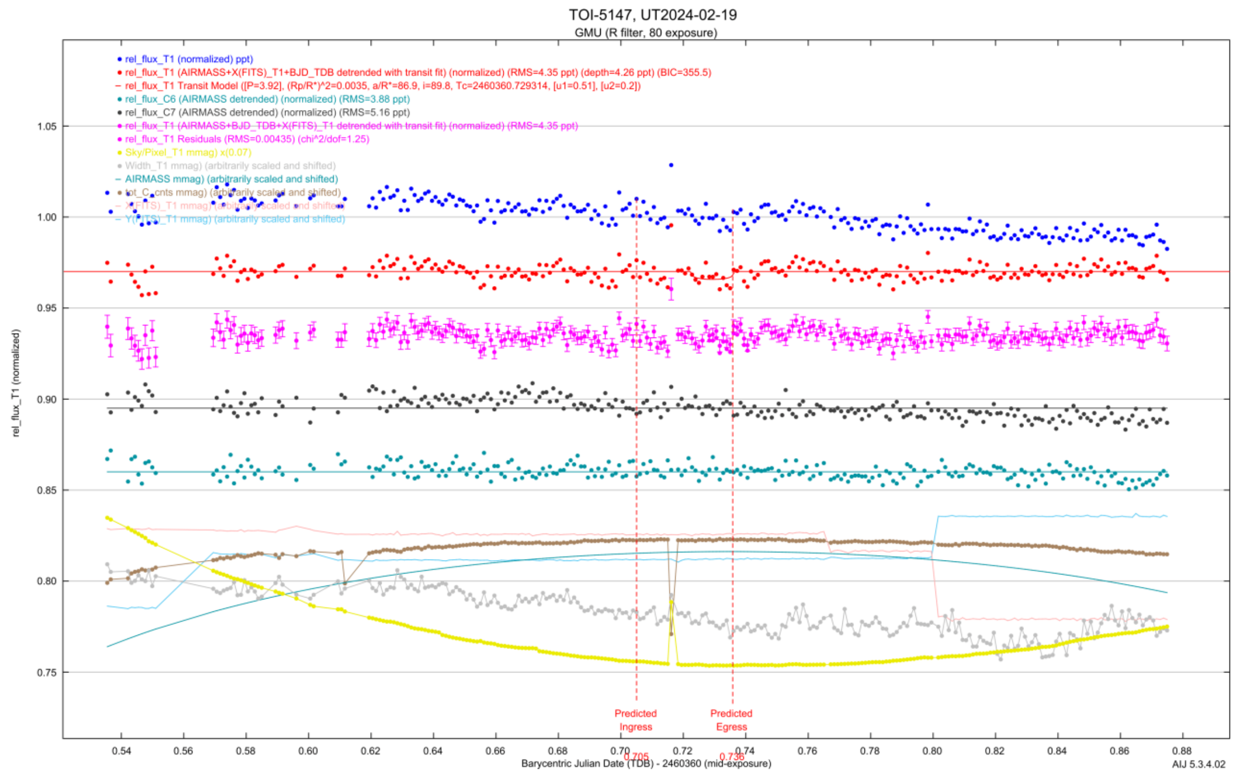

Figure 5. *The final light curve. The blue curve is the relative flux of the target star with no changes or modifications. The red curve is the detrended blue curve fitted to the model, and the magenta curve are the errors for red curve, separated for visual clarity. The black and teal curves are the graphs of the reference stars, and all of the curves underneath are related to external conditions which can be used for detrending.*

scaling, auto-x range is chosen to view the data in a reasonable window. In the Fit and Normalize Region Selection, the copy button is clicked to make the V.Marker 1 and V.Marker 2 appear as vertical dotted lines.

Now we move to Data Set 2 Fit Settings, where the target's period should be entered in the Orbital Parameters section, and the host star radius should be entered in the Host Star Parameters section. Next, the Linear LD u1 and Quad LD u2 should be inputted in the Transit Parameters. It's important to make sure all detrend parameters are unchecked at this point. Under Plot Settings, both "Show Residuals" and "Show Error" should be checked.

Under Multi-plot Y data, check all of the following "Plot" boxes: Sky/Pixel_T1, Width_T1, AIRMASS, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1. Each of these curves were set to a scale of 15 (except for AIRMASS, which should be -15), varying shift values so they would all appear at once, with different colors to distinguish them. The colors and shift values were chosen according to Dennis M. Conti's TFOP SG1 Observation Guidelines document [6]. Page relative (just to the left of scale) is also checked for each of these curves. After this, check each reference star's light curve; if any of them are too scattered, uncheck them in the "Multi-Plot Reference Star Settings" window.

If the .radec file was present before the multi-aperture photometry was performed, then go to the File navigation bar at the top of Multi-Plot Main and choose Create NEB search reports and plots.

Next, the process is to look at every combination (preferably 3 or less) of detrending parameters and choose which combination minimizes the RMS value and

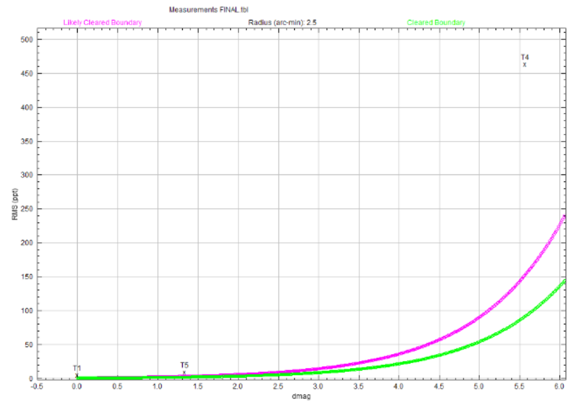

Figure 6. *The dmag vs. RMS plot generated from the NEB report. To eliminate the nearby stars as possible sources of false-positives, all T stars would need to be under the green "cleared" boundary.*

makes the transit most accurate to the TESS data. Due to the possibility of a false-positive occurring, another test is needed: this is the p-value (statistical) test.

4. Results

The above light curve (Figure 5) is the result of the analysis after detrending was done with the AIRMASS, X(FITS), and BJD_TDB plots. There is a discernable transit with a depth of 4.26 ppt, which lines up closely with the TESS' value[3] of 4.27 ppt, within its error of ±0.02 ppt. The calculated transit duration of 20.63 minutes doesn't fall within the TESS' duration and its associated error of 44±9 minutes. And the start of the transit is 23 minutes after the predicted ingress time, which doesn't fall within the margin of error, which is 4 minutes. However, the end of the transit is aligned with egress time. Another point to mention is that the root mean square (RMS), which is one measure of scatter compared to the compared model, is greater than the transit depth; the RMS was 4.355 ppt, while the transit was 4.26 ppt.

Furthermore, a statistical test was done to discern the true nature of the transit. Using the chi-squared value provided from the Data Set 2 Fit Settings window, 322.0614, and the degrees of freedom (255) the two-tailed p-value for a given confidence interval is calculated [7]. This p-value is used to determine whether or not the results are significant at this confidence interval. At an interval of 0.01, or 99% confidence, the p-value is 0.00557.

This comes with the caveat of the uncleared NEBs; none of the surrounding stars were cleared as being not an NEB, including the target star. See Figure 6.

5. Discussion

The interpretation of this light curve leads to mixed results, as some of the model's calculated values conflict with information from TESS, or don't fall within the margin of error for the calculated parameters, but others show promise. For example, the transit duration is 20.63 minutes, which does not fall within the error of .144 hours of the calculated duration of .739 hours. But the transit depth of 4.26 ppt is more than the lower limit of 4.25 ppt of the transit depth. There is another complication regarding the transit depth and stellar parameters; AIJ doesn't seem to be able to properly compute all of the stellar parameters simultaneously. In the Data Set 2 Fit Settings (which is the window to adjust the transit model), there are inputs for host star properties, these being radius, mass, and temperature. For these inputs, one is entered and the others are automatically calculated, where the formula changes according to spectral type. The spectral classification choices are all in the form of _ _ V, meaning they are all treated to be main sequence stars. In addition, for each spectral type (OBAFGKM), they are split into two subdivisions of _0V and _5V. TOI-5147 has an effective surface temperature of 5174.39 K, a radius of 0.877, and mass of 0.877 as compared to the Sun. Compared to what is considered the spectral standard for K0V

(Sigma Draconis), TOI-5147 has a lower surface temperature but greater mass and radius. Yet its specifications are not close enough to the Sun to be considered G0V. Due to the numerical subclassification decreasing in number with greater temperatures, G5V and K0V are the two closest matches for TOI-5147. However, under either of these choices, all of the star properties cannot be correct simultaneously; if star radius is entered, then temperature and mass will be off, and vice versa. While this doesn't influence everything (transit depth remains unchanged, for example), transit duration and planetary radius are changed. For example, the planetary radius as calculated by this model is 0.52 Jupiter radii (R_j) while TESS' numbers give a value of 0.631 R_j despite the depth being nearly identical.

All of this said, the start of the transit according to the model is 23 minutes after the ingress time, which is later than the margin of error allowed, being 4 minutes. Yet the transit endpoint lines up with the egress time. The model's RMS is also greater than the transit depth, meaning the transit seen could be due to chance from the scatter of the data and not a legitimately detected transit; it can't be stated with certainty that the transit actually exists. But due to how close these two values are, there is a high probability that a transit has been detected. The uncleared NEBs as well don't mitigate the possibility of a nearby eclipsing binary influencing the light curve of TOI-5147.01. Only three of them could actually be plotted, and none cleared the test. Two of them had fluxes too low (T2 and T3). T1 and T5 are just above the likely cleared boundary, and were not cleared. T4 would be considered an outlier. While this doesn't mean that the stars in the surrounding 2.5' radius are NEBs, we can't conclusively say that they aren't; these neighboring stars could still be potential sources for false-positives.

Another thing to consider is the results of the statistical test. A p-value of 0.00557 at a confidence of 99% bodes well for the validity of these results, as this implies statistical significance. Let us take the null hypothesis as: any observed variation in the data is purely due to chance; there is no reason for these differences, it is entirely random. The statistical significance allows us to reject the null hypothesis and accept the alternative hypothesis, which is that the effect is real, and the results are attributable to a specific cause. The low chi-squared over DOF value being close to 1, at 1.25, is a good sign as well.

All of this leads to inconclusive evidence of a transit. While everything introduced doesn't definitively point to a transit, we believe there is enough here to warrant future research.

6. Conclusion and Future Work

We haven't seen enough from our analysis to say that a transit occurred, but some signs present show that there is sufficient reason for future research to be justified. The transit depth, RMS and the statistical tests imply statistical significance, but the duration and failed NEBs add uncertainty or don't rule out the possibility of a false positive.

We would suggest that any future work involve taking images at a slightly different angle where the target is more centered in the sciences, due to the choice of the previous sciences placing the target near the edge of the field of view, which can lead to neighboring stars dipping out of view. This target is in a relative sparse zone, with not a lot of neighboring stars in its close vicinity or close to one another, so this may have been done for the sake of enough stars being present for multi-aperture photometry.

We also put forth the idea of using a wider field of view so more stars can be used for multi-aperture photometry. Also, if possible, two sets of sciences should be taken, one of which focuses on the target and the other focuses on its nearby stars to properly identify them as NEBs or not. There is only one star within a 2.5 arcminute radius of TOI-5147.01 that is bright enough to be used for an NEB check; this would make it easy to eliminate or confirm any nearby stars as NEBs.

Future analysis could involve running ExoFAST to produce probability distributions about this system, which could reveal more about the possibility of these results being a false-positive. If multiple transits could be recorded across a longer time-span, assuming they all aren't even or odd integer transits, an even-odd test could be performed to ensure that the transit seen is because of a planet passing in front of its host rather than another form of transiting binary system.

References

[1] Davoudi, F., Jafarzadeh, S. J., Poro, A., Basturk, O., Mesforoush, S., Harandi, A. Fasihi, Gozarandi, MJ., Mehrjardi, Z. Zare, Maley, P. D., Khakpash, S., Rokni, K., Sarostad, A. (2021, August). Light Curve Analysis of Ground-Based Data from Exoplanets Transit Database. CrossRef

[2] Xiao, C., Xiao, A., Collins, K., & A., S. (2023). (P. Plavchan, Ed.). *Journal of Astro-Scholars Research at George Mason University*, *1*, 164–173. CrossRef

[3] TESS, & ExoFOP. (2022). *TOI-5147 Overview*. TOI-5147 | NASA Exoplanet Archive. CrossRef

[4] TESS. (2024). *TOI-5147*. Exofop TIC 95361530. CrossRef

[5] Collins, K. A., Kielkopf, J. F., Stassun, K. G., & Hessman, F. V. (2017, February). AstroImageJ: Image Processing and Photometric Extraction for Ultra-Precise Astronomical Light Curves - Astrophysics Data System. CrossRef

[6] Conti, D. M. (2024, September 4). TFOP SG1 Observation Guidelines. CrossRef

[7] *P-Value Calculator*. Quick P-Value Calculator | 365 Data Science. (n.d.). CrossRef