Ground-Based Light Curve Follow-Up Validation Observations of TESS Object of Interest 5147.01

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Abstract

Exoplanet research is essential for understanding how planetary systems fit into our universe. Through the Transiting Exoplanet Survey Satellite (TESS) mission, many exoplanet candidates were found, but few have been confirmed. The purpose of this paper is to verify the existence of TESS Object of Interest (TOI) 5147.01 using the transit method. We took ground-based observations at George Mason University of the host star, TOI 5147, then created a light curve using AstroImageJ. A nearby eclipsing binary (NEB) check was conducted using AstroImageJ to analyze stars within a 2.5" of the host star. This is then followed by a Markov chain Monte Carlo (MCMC) analysis to calculate output parameters and their uncertainties. The AIJ lightcurve provides strong evidence for the existence of TOI 5147.01. However, there are still uncertainties for the transit timing and planet parameters for TOI 5147.01.

1. Introduction

The study of exoplanets has exponentially increased in the astronomy field ever since the 1992 discovery of two exoplanets orbiting a radio pulsar (Wolszczan & Frail, 1992). In the 32 years since, scientists and astronomers have confirmed over 5,700 exoplanets using a large variety of scientific methods and tools (NASA Exoplanet Archive, n.d.). For instance, Mayor & Queloz detected the exoplanet 51 Pegasi b using the radial velocity technique and classified it as a 'hot Jupiter' in 1995. This radial velocity technique aided in the discovery of approximately 1000 exoplanets. This crucial method consists of analyzing the change in wavelength from the target star as it moves to and fro in reaction to the exoplanet's gravitational force over time. Nevertheless, the transit method is responsible for 70 percent of all validated exoplanet candidates, in which a dip in flux from a target star occurs as an exoplanet transits in front of it. Multiple missions use this transit method to search for and validate exoplanet candidates such as NASA's 2009-2013 Kepler mission as well as today's Transiting Exoplanet Survey Satellite (TESS) mission (In Depth: Exoplanets, n.d.). TESS launched in 2018 with the mission to survey over 200,000 nearby stars for exoplanets using the transit method. A wide variety of exoplanets have been and continue to be discovered using TESS, including hot Jupiters, super Earths, and Neptunian worlds (Transiting Exoplanet Survey Satellite (TESS), n.d.).

Using TESS, NASA has identified over 7,200 exoplanet candidates as of July 2024. However, only 542 candidates are classified as confirmed exoplanets (NASA Exoplanet Archive, n.d.). More follow up observations are required to validate the overwhelming number of exoplanet candidates. TESS has a resolution of roughly 21 arcsecs per pixel in the sky (Characteristics of the TESS Space Telescope, n.d.). With this resolution, it is not uncommon for

TESS to mistake a nearby eclipsing binary (NEB) as an exoplanet transit. Ground-based update observations are required in order to verify that the TESS object of interest (TOI) does have a true positive exoplanet transit signal. Additionally, these follow up observations can give us the opportunity to understand more about the exoplanet conditions: such as its planet type, atmosphere, and whether or not it can sustain life.

In December of 2023, the TESS Science Processing Operations Center (SPOC) published a Data Validation report for TESS ID 95361530 (TOI 5147.01) using the light curves collected from TESS. TESS collected data on three different occasions in sectors 45, 46, and 72. The observed transit has a duration of 1.1444 hours and planet radius of 0.5529 Jupiter radii (SPOC, 2023). With the predicted parameters being 0.739±0.144 hours and 0.631±0.051 Jupiter radii, the Data Validation report conducted by SPOC did not produce matching results for TOI 5147.01 (TOI 5147.01 Overview, n.d.). Further observation and analysis is required to provide more insight on the transit and planetary parameters of TOI 5147.01.

In this paper, we present TOI 5147.01. This planet revolves with a period of 3.92 days around the K class host star, TOI 5147. The predicted radius of TOI 5147.01 is 0.631±0.051 Jupiter radii with a depth percentage of 0.427% (4.3 ppt) (TOI 5147.01 Overview, n.d.). The goal of this paper is to confirm that TOI 5147.01 transits TOI 5147 on February 13, 2024 within the predicted ingress/egress estimates and with the estimated depth and planetary parameters.

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 5147.01 and our ground-based light curve analysis. In Section 4, we present our light curve results. In

Section 5, we discuss our results. Lastly, in section 6, we present our conclusions and future work.

2. Observations

In Section 2.1 we present the TESS Object of Interest 5147.01, 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 curve(s). In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1 TOI 5147.01 and Archival Sources

Observations of TOI 5147.01 were first conducted during TESS's fourth year in November of 2021 (MAST, n.d.). Host star TOI 5147 is a K class star with an effective temperature of 5174.3900±100.009 K and a radius of 0.88±0.04 sun radii (ExoFOP, n.d.). Further stellar parameters of TOI 5147 are shown in figure 1 below. TOI 5147 has a right ascension of 10:16:57.85 and a declination of +18:12:50.27.

Solar Parameter	Value	Source
Effective Temperature [K]	5174.39 ± 100.009	ExoFOP
Radius [R Sun]	0.88 ± 0.04	ExoFOP
Mass [M Sun]	0.877 ± 0.1034	ExoFOP
Metallicity [Fe/H]	0.308 ± 0.034	ExoFOP
Stellar Log(g) [cm/s^2]	4.4946 ± 0.07551	ExoFOP

Figure 1: Table of solar parameters on TOI 5147.

Transit/Planet Parameter	Value	Source
Start-Mid-End [TBJD]	10360.7050 103060.7204 103060.7358	TESS Input Catalog
Duration [hours]	0.739 ± 0.144	ExoFOP
Depth [ppt]	4.27 ± 0.0204	ExoFOP
Depth [%]	0.427 ± 0.00204	Exoplanet Archive
Period [days]	3.918 ± 0.00009280	ExoFOP
Planet Radius [R Jupiter]	0.6317	exo.MAST
Planet Equilibrium Temp [K]	1083.23	exo.MAST
Semi Major Axis (a/Rs) [stellar radii]	11.409	exo.MAST

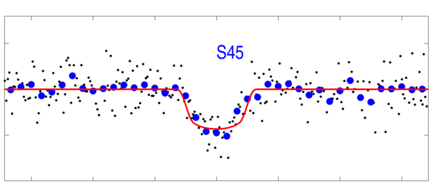
Figure 2: Table of transit and planetary parameters of TOI 5147.01

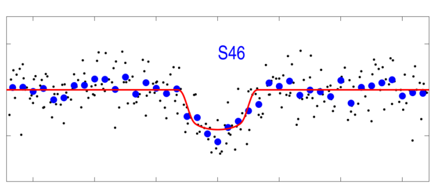
Furthermore, Figure 2 shows the predicted planet and transit parameters for TOI 5147.01. For the planet radius and equilibrium temperature, multiple sources show different values, so these predicted values in the table below come from the most recently updated source, exo.MAST. The rest of the predicted parameters, including the stellar parameters, were equivalent among all sources or were only found on the source cited in the tables. Many of these parameters come from ExoFOP, the Exoplanet Follow-up Observing Program, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. Exo.MAST gives exoplanet parameters given by MAST (Mikulski Archive Space Telescopes), a NASA funded project to hold data from numerous space telescopes.

Additionally, this paper uses information gathered by Gaia, an European space mission with the purpose of gathering information on over 2000 million stars (Gaia Archive, n.d.). The Gaia ESA Archive provides position, brightness, radial velocity, etc. measurements of these stars, and this paper used this archive to aid in multi-aperture photometry and nearby eclipsing binary (NEB) checks.

2.2 TESS Light Curves

TESS conducted first observations of TOI 5147.01 on November 7, 2021 in sector 45 from November 7, 2021 to December 2, 2021. Further observations were conducted in sector 46 from December 3, 2021 to December 30, 2021 and then sector 72 from November 11, 2023 to December 7, 2023 (MAST, n.d.). TESS Science Processing Operations Center (SPOC) published a Data Validation (DV) report for TOI 5147.01 using the light curves generated from these three observations. Figures 3-5 show the individual light curves from each sector, while figure 6 shows the folded and averaged light curve (SPOC, 2023).





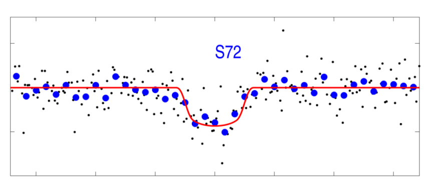


Figure 3: Sector 45

Figure 4: Sector 46

Figure 5: Sector 72

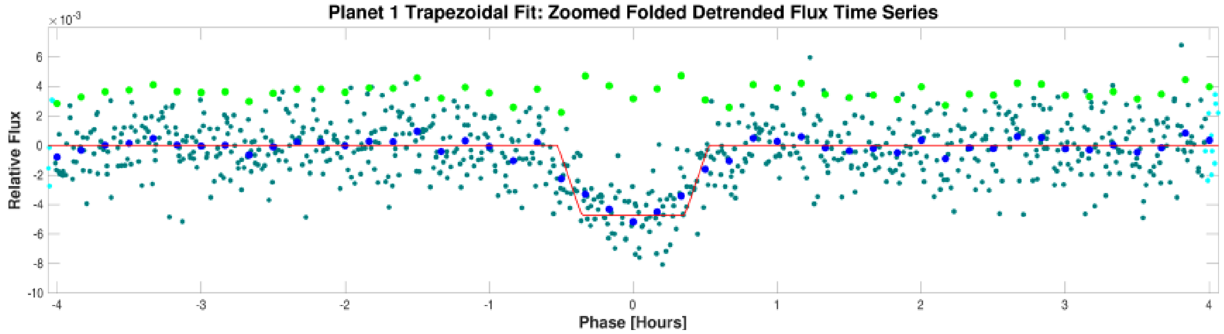


Figure 6: The folded light curve of all three sectors

2.3 Data Collected From Ground Observations

Data collection at George Mason University's Fairfax campus began on February 19, 2024 at 23:48 UTC and ended on February 20, 2024 at 10:56 UTC. We used George Mason's 0.8m telescope with an R filter. We took 296 science images with an 80s exposure length, ten 3.5s flats, ten 80s darks, and ten 3.5s darks.

3. Analysis

In Section 3.1 we present the tools used to analyze the TESS sector light curves from the DV report. In Section 3.2, we present our analysis of the ground-based light curve using AstroImageJ and ExoFAST.

3.1 TESS Light Curve Analysis

The DV Report first took the data collected by TESS and created a raw flux time series with transit events for each of the three sectors. A pixel level diagnostic was then conducted to create multi-sector average PRF fits of the different images. Next, SPOC created folded light curves (Figure 6) using the lightcurves from each sector (Figures 3-5), as well as even and odd light curves. In this step, SPOC also conducted an Eclipsing Binary Discrimination Test, Ghost Diagnostic Test, Difference Image Centroid Offsets, and a Bootstrap Test. Finally, SPOC used a model fitter to create a Model FItter Block to produce parameters such as period, depth, etc. and the likelihood of an exoplanet using the results of the lightcurves and previous tests. A more detailed showcase of the analysis can be read from the DV Report for TESS ID 95361530 (SPOC, 2023).

3.2 Analysis Using AstroImageJ and ExoFAST

The first step we took was to take out any science images that would interrupt our light curve. Out of 296 sciences,34 images were taken out, mainly within the first hour and a half of data collection, for a total of 262 usable sciences. The next step we took was to use AstroImageJ (AIJ) to reduce and plate solve our data: this process consisted of dark subtraction and then flat division to reduce as much noise as possible (Collins et al., 2016). AIJ simultaneously platesolved each science using astrometry.net to identify the location of the target star and its neighboring stars. This ensures that the lightcurve extraction comes from the correct star even when the telescope might have shifted.

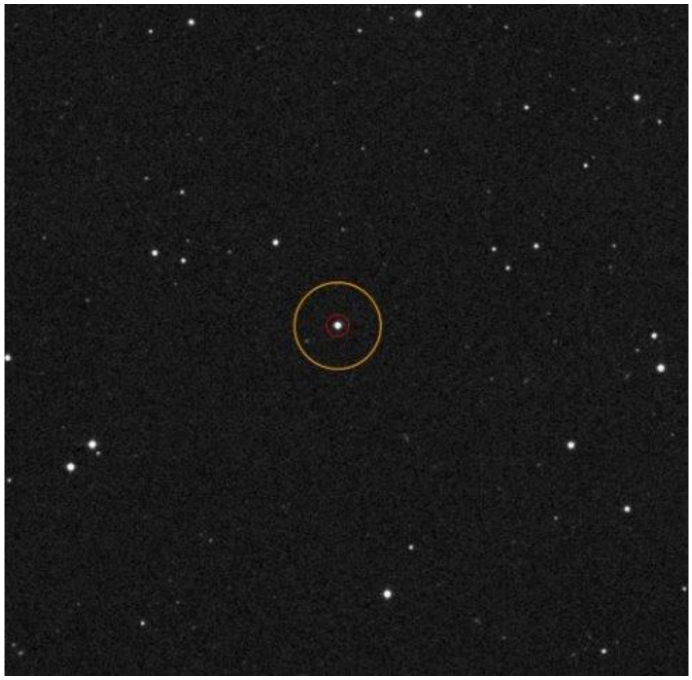


Figure 7: TOI 5147

The first step to lightcurve extraction is Multi-Aperture Photometry. To find the radius of the apertures, AIJ created a “Seeing Profile” (shown in Figure 8) based on the observed HWFM of the ADU of the target star. The Seeing Profile results are as follows: radius of 23px (8.326”), inner annulus of 40px, and outer annulus of 59px. The stars downloaded previously from the Gaia Archive are then imported; these stars are specifically imported to be within 2.5’ of the target star for later NEB checks. After importing the Gaia stars, multiple apertures are then placed around comparison stars of similar brightness to the target star. We used the Online Digitized Sky Surveys server at the ESO Archive to initially locate where the target star is to place its aperture (ESO, 2022). Figure 9 shows the red apertures around comparison stars and green apertures around the Gaia stars. Once aperture placement is complete, AIJ creates a measurements table which is used for the lightcurve graph. We used a light curve graph format that follows the TESS/K2 reporting guidelines (Conti, 2016). Additionally, we found our limb darkening coefficients using ExoFAST (Eastman et al, 2013). For the lightcurve, we used the detrending parameters of Width, X(FITS), and Y(FITS).

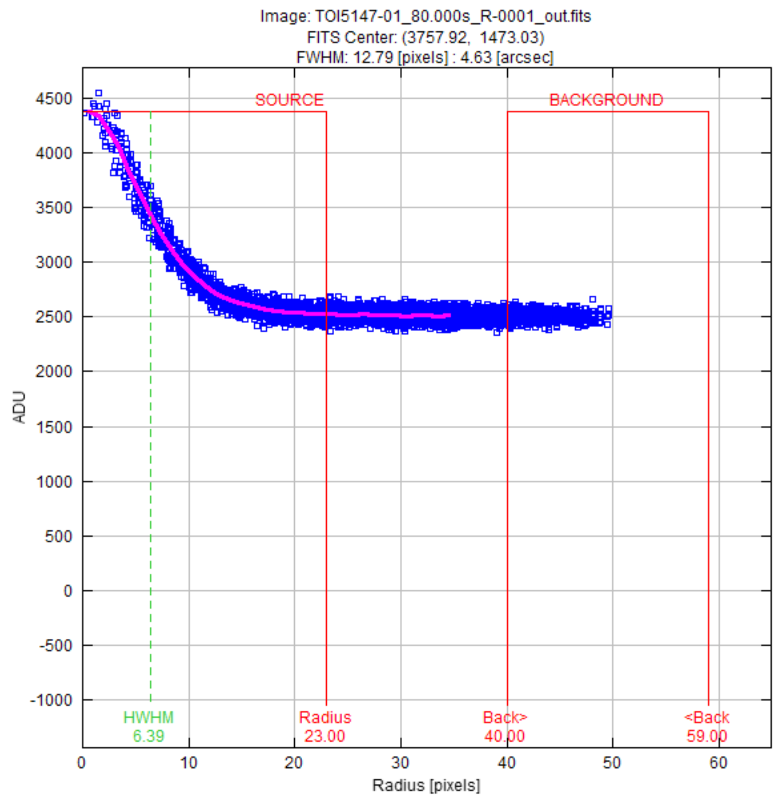


Figure 8: Seeing profile of TOI 5147

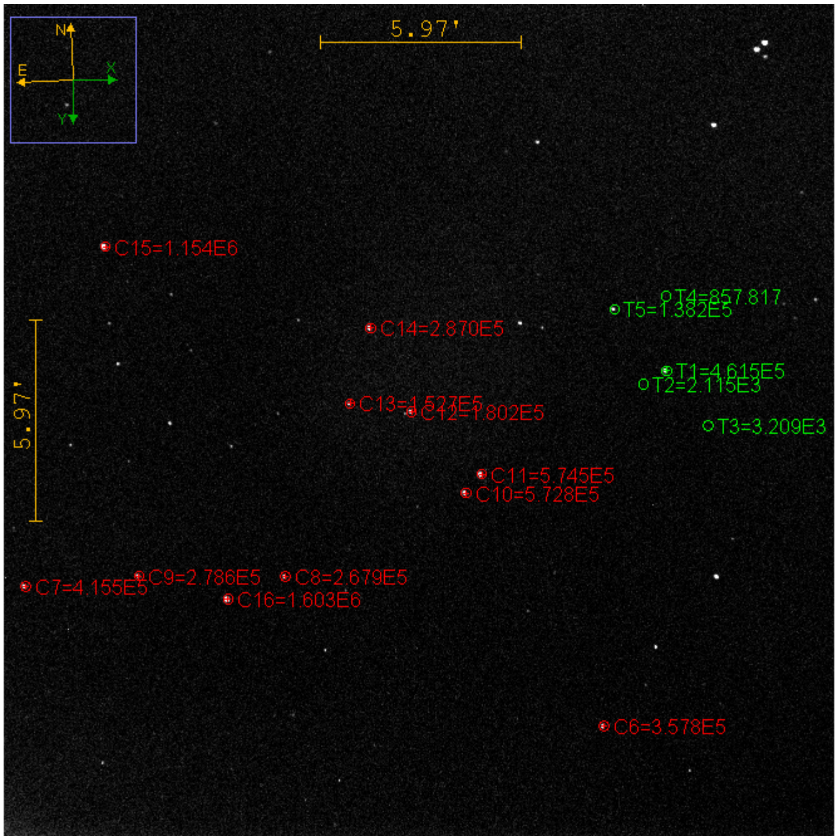


Figure 9: Apertures used for lightcurve extraction

We then conducted nearby eclipsing binary (NEB) checks in AIJ to ensure that our lightcurve came from the target star alone. As stated before, the Gaia star apertures are used to create a dmag vs. RMS plot which showcases if nearby stars are cleared by the NEB check or fail. Additionally, AIJ created individual normalized flux vs. time graphs for each of the nearby Gaia stars to check for transits. Further instructions on our process of using AIJ can be found on Dr. Peter Plavchan's AIJ Tutorial (Plavchan, 2024) as well as TFOP SG1 Observation Guidelines (Conti, 2020).

We used Jason Eastman's ExoFASTv1 to conduct a Markov chain Monte Carlo (MCMC) analysis to create probability distribution charts for output parameters (Eastman et al., 2013).

After importing our measurements table from AIJ into ExoFAST, we copied the best fit priors and prior widths from AIJ into ExoFast along with predicted solar and transit parameters. More detail about the inputs used for ExoFastv1 is written in ExoFast's original paper (Eastman et al., 2013).

4. Results

In section 4, we present our results given from AstroImageJ and ExoFASTv1. Figure 10 shows the light curve extracted from AIJ, Figure 11 shows the dmag vs. RMS plot from AIJ's NEB checks, Figures 12-13 show the flux vs. time plots for potential sources of NEBs, FIgure 14 shows some of the distribution plots given by the MCMC analysis, and Figure 15 shows the resulting values of the MCMC analysis.

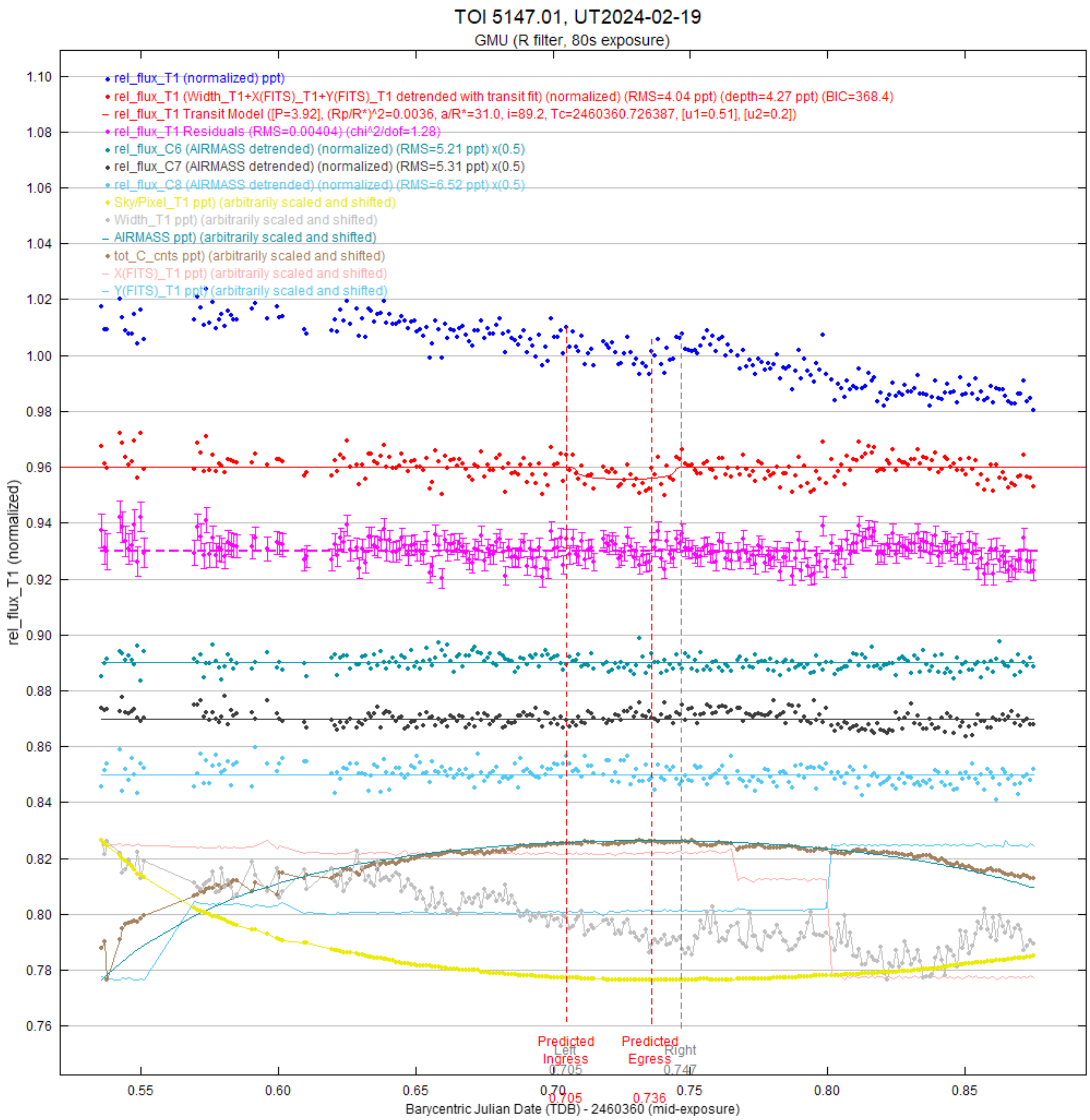


Figure 10: AIJ light curve

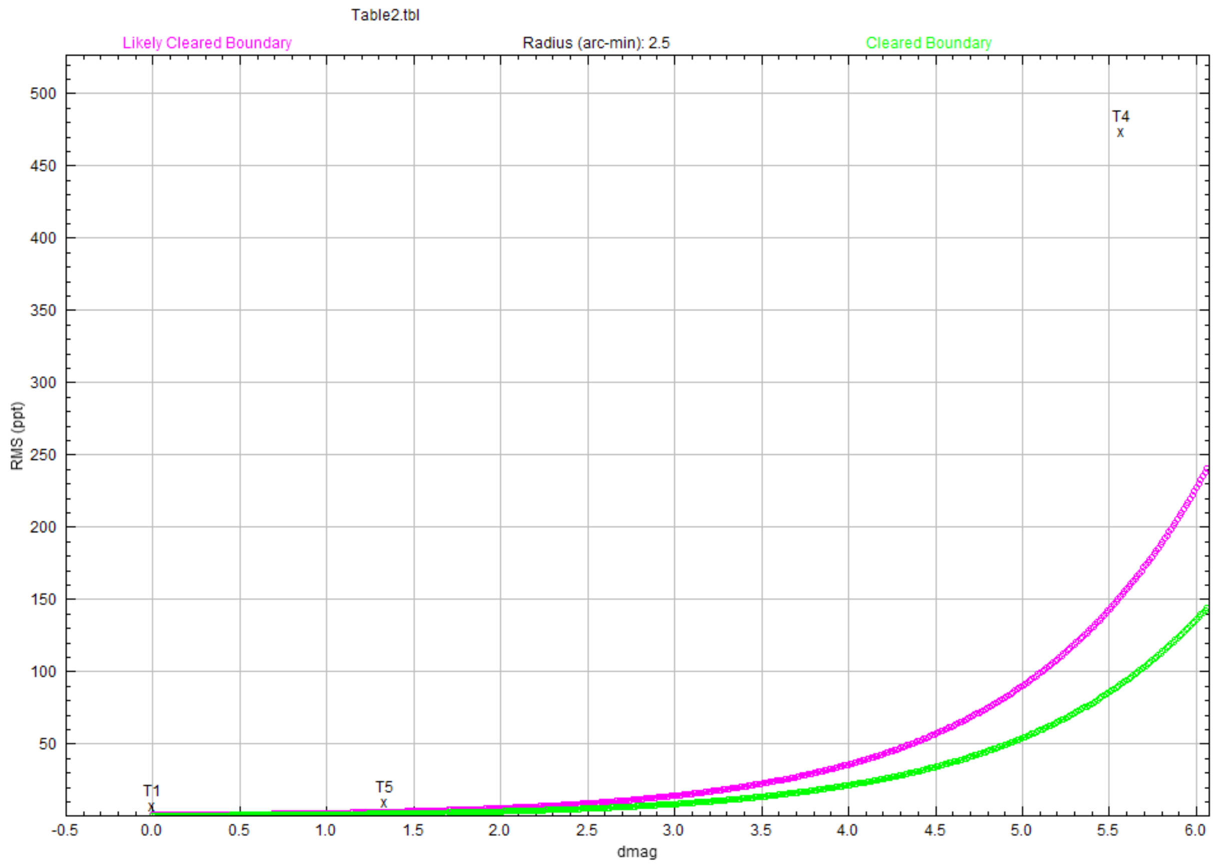


Figure 11: dmag vs. RMS plot for NEB checks

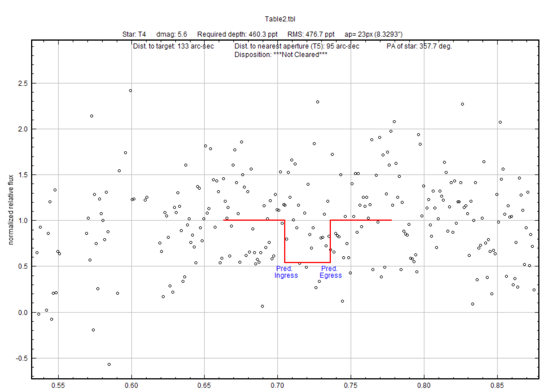


Figure 12: T4 light curve

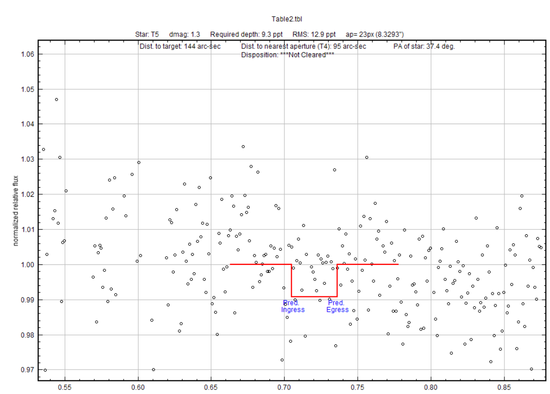


Figure 13: T5 light curve

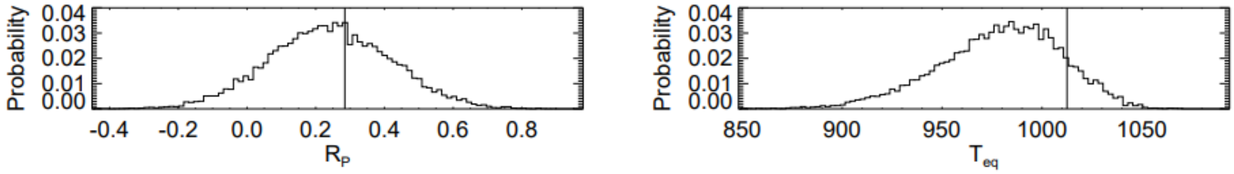


Figure 14: Probability distributions of planet radius and equilibrium temperature

symbol	parameter	units	value	upper_error	lower_error
char	char	char	double	double	double
M*	Stellar Mass	Msun	0.897420	0.052964	0.050093
R*	Stellar Radius	Rsun	0.733811	0.031751	0.044539
L*	Stellar Luminosity	Lsun	0.340115	0.049368	0.049285
rho*	Stellar Density	cgs	3.205274	0.603371	0.348024
logg*	Stellar Surface Gravity	cgs	4.660133	0.049217	0.032480
Teff	Effective Temperature	K	5159.649384	103.774177	97.436220
FeH	Metallicity	none	0.301709	0.078212	0.079985
P	Period	days	3.917860	0.000092	0.000093
a	Semi-Major Axis	AU	0.046903	0.000905	0.000890
Rp	Planet Radius	Rj	0.246486	0.182937	0.174420
Teq	Equilibrium Temperature	K	982.477839	27.849406	33.583964
Fave	Incident Flux	10^9 ergs s^-1 cm^-2	0.211332	0.025000	0.027448
TC	Time of Transit	BJD	2467360.726001	0.001673	0.001600
Rp/R*	Radius of Planet in Stellar Radii	none	0.034734	0.025775	0.024549
a/R*	Semi-Major Axis in Stellar Radii	none	13.748032	0.813250	0.516449
u1	Linear Limb-Darkening Coeff	none	0.511369	0.052658	0.053150
u2	Quadratic Limb-Darkening Coeff	none	0.194387	0.050535	0.050466
i	Inclination	degrees	79.275389	7.568271	11.728869
b	Impact Parameter	none	2.569577	2.727357	1.804529
delta	Transit Depth	none	0.001220	0.002442	0.001058
TFWHM	FWHM Duration	days	0.000000	0.057910	0.000000
tau	Ingress/Egress Duration	days	0.000000	0.001988	0.000000
T14	Total Duration	days	0.000000	0.062979	0.000000
PT	A Priori Non-Grazing Transit Prob	none	0.070002	0.003305	0.004192
PTG	A Priori Transit Prob	none	0.075137	0.003433	0.004484
F0	Baseline Flux	none	0.995557	0.001035	0.001061
TS	Time of Eclipse	BJD	2467362.684929	0.001678	0.001600

Figure 15: ExoFAST MCMC parameter results

5. Discussion

In Section 5.1 we present our interpretation of our results. In Section 5.2 we place our results into context of the greater field of follow-up of candidate exoplanets from the NASA TESS mission.

5.1 Interpretation of Results

Our results from AIJ point to the conclusion that TOI 5147.01 is a likely exoplanet, but the output parameters did not align with the predicted ones. Our red detrended light curve shown in Figure 10 has a chi squared per degree of freedom value of 1.280, an RMS 4.04, BIC of 368.4, and a Two Tailed P-Value: 0.0017. Stated in table of Figure 16, the fitted light curve in Figure 10 has a depth of 4.27 ppt; this is the exact value of the predicted depth value for TOI 5147.01, meaning that it is very likely that this is an exoplanet lightcurve. Looking at the table in Figure 16, the measure ingress started at the same time as the predicted value. However, the egress happened roughly 16 minutes after the predicted egress, causing the total duration to be 16 minutes longer than the predicted duration; this is beyond the error of the predicted duration time. Another parameter that has questionable results is the planet radius. The predicted value is 0.6317 R Jupiter, but the measured value is 0.51. The measured depth percent, which is calculated using the planet radius, is also noticeably smaller than and outside the error of the predicted depth percent. Drastic differences are also seen with the predicted vs. measured semi major axis.

	Start-Mid-End [TBJD]	Duration [hours]	Depth [ppt]	Depth [%]	Planet Radius [R Jupiter]	Semi Major Axis (a/Rs) [stellar radii]
Predicted Value	10360.7050 103060.7204 103060.7358	0.739 ± 0.144	4.27 ± 0.0204	0.427 ± 0.00204	0.6317	11.409
Measured Value [AIJ]	103060.7050 103060.7264 103060.7470	1.00	4.27	0.3596	0.51	30.9796

Figure 16: Table of predicted and measured values from AIJ

With the NEB check analysis done by AIJ, results came as inconclusive. Out of the four Gaia stars that were checked for NEBs, two stars were too faint to deem as clear, and the other two did not pass the NEB check. Although these stars did not mathematically pass the NEB check, the stars do not have any noticeable light curves in FIgures 12-13, and they do not have any outlying positions from the boundaries on the dmag vs. RMS plot in Figure 11. With this in mind along with the previous statistical values stated, it is unlikely that the measured light curve is a false positive.

Figure 17 shows some of the results of the MCMC analysis in comparison with predicted values. For the transit midpoint, the MCMC measured value is very similar to the measured value from AIJ. However, as stated previously, this value is noticeably later than the predicted value. For the measured planet radius and depth percent, these values are significantly smaller than the predicted values, even with the upper error included. The measured semi-major axis is larger than the predicted value, but it is much more realistic compared to the value from AIJ. However, the MCMC results have a chi squared per degree of freedom of 13.062 for the priors. Additionally, a plenitude of Torres relation and limb darkening warnings appeared in the log after the analysis was complete, advising that these results are likely questionably and unreliable.

	Predicted Value	Measured Value (MCMC)	Upper Error	Lower Error
Transit Midpoint [TBJD]	103060.7204	103060.7260	0.001673	0.001600
Depth [%]	0.427 ± 0.00204	0.1220	0.2442	0.1058
Planet Radius [R Jupiter]	0.6317	0.246486	0.182937	0.174420
Semi Major Axis (a/Rs) [stellar radii]	11.409	13.748032	0.813250	0.516449
Semi Major Axis (a/Rs) [AU]	N/A	0.046903	0.000905	0.000890
Equilibrium Temp [K]	1083.23	982.477839	27.849406	33.583964

Figure 17: Table of predicted and measured values from ExoFAST's MCMC analysis

5.2 In the Context of the Greater Field

We compare our results with the 2023 DV report as well as previous notes on the TESS Input Catalog. As stated previously, the DV report did not provide matching results with predicted parameters for TOI 5147.01. However, our results are similar to the DV output results, shown in Figure 18, on numerous occasions. The transit duration from the DV report is 1.1444 hours, and our measured duration from AIJ is 1 hour exact; both of these comparable values are noticeably longer than the original predicted transit duration. The DV report also states similar values to our results but are different from those predicted with planet radius: 0.5529 R Jupiter (6.1970 R Earth) and equilibrium temperature: 991 K.

Parameter	Value	Uncertainty	Units
SNR	21.7		
Orbital Period	3.9180768	9.3951e-06	days
Transit Epoch	2526.1840021	6.6505e-04	BTJD
Impact Parameter	0.6995	5.8819e-01	
Planet Radius to Star Radius Ratio	0.0646907	1.1597e-02	
Semi-major Axis to Star Radius Ratio	21.0100	1.6569e+01	
Planet Radius	6.1970	1.1550e+00	Earth radii
Semi-major Axis	0.0466	3.1304e-03	AU
Effective Stellar Flux	227.8982	3.2686e+01	Goldilocks
Equilibrium Temperature	991	3.5532e+01	Kelvin
Stellar Density	8.1165	1.9202e+01	Solar density
Transit Depth	4342	2.1918e+02	ppm
Transit Duration	1.1444	1.9815e-01	hours
Transit Ingress Duration	0.1296	2.3266e-01	hours
Eccentricity	0.0000	0.0000e+00	
Peri Longitude	0.0000	0.0000e+00	degrees
Model Chi Square Statistic (DoF)	437.5 (591.5)		
Model Chi Square Goodness of Fit Statistic (DoF)	63.6 (133)		
Model Chi Square2 Statistic (DoF)	9.4 (16)		

DoF: Degrees of Freedom

Figure 18: SPOC DV parameters table

With the AIJ measured radius being 0.51 R Jupiter (5.7165 R Earth), TOI 5147.01 between the size of Uranus and Saturn (*Solar System Sizes*, 2003). Additionally, the measured equilibrium temperature from the MCMC analysis is 982.477839 K. Exoplanets with an equilibrium temperature greater than 800 K and a radius of 4.5-7.5 R Earth were mostly found as sub-Saturns. These gas giants have a mass ranging between 15-40 Earth Masses (Russell, 2023). Sub-Saturns are very diverse in mass and size and are more prone to having moderate eccentricities and be part of single planet systems (Petigura E. A., et al. , 2017).

6. Conclusion and Future Work

Using AstroImageJ, we generated a light curve of TOI 5147 for a confirmation on the existence of exoplanet TOI 5147.01. Using the priors from AIJ, we further conducted an MCMC analysis using ExoFAST to calculate output parameters and their uncertainties. The AIJ lightcurve shows strong evidence of exoplanet existence, but the duration is longer than predicted values. The MCMC analysis shows support for certain parameters from AIJ and previous sources, but errors during the analysis show that these results are likely questionable. The NEB check comes back as inconclusive when searching for sources of false positives.

Although there is strong evidence for the existence of TOI 5147.01, more observations and research needs to be conducted for a better understanding of planet characteristics. Further observations on transit timing can be done to solidify the transit timing. Additionally, further calculations are required to grasp a better understanding of the exoplanet parameters and exoplanet type. A more complicated analysis can be conducted to get an accurate analysis on nearby stars to statistically rule out false positives. Moreover, the radial velocity method can be carried out to calculate values beyond the transit method such as planet mass and density.

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