Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest TOI 5356.01

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Abstract

The Transiting Exoplanet Survey Satellite (TESS) is a NASA mission which identifies candidate exoplanets using the transit photometry method. These exoplanets must then be verified using ground-based telescope follow-up observations. This paper presents the results of a follow-up observation on TESS Object of Interest (TOI) 5356.01, with the aim of verifying characteristics of its predicted transit. Our analysis demonstrates that the transit occurred within expected parameters and our observations were sufficiently accurate, supporting the existence of TOI 5356.01 as an exoplanet.

1 Introduction

Exoplanets are an important topic of study in astronomy, providing insight into planetary system formation. Since the first exoplanets were discovered in 1992, researchers have identified thousands of worlds, some of which theoretically have the conditions to sustain life [1]. The technology used to identify exoplanets has also evolved: while a majority of detections before 2014 were made using radial velocity, transit photometry has since become the dominant method to find exoplanets [2]. When an exoplanet passes, or "transits", between its host-star and an observer, it partially blocks the light from the star. This creates a measurable decrease in the light from the star, which can indicate the existence of the exoplanet and be used to predict its characteristics. The TESS satellite, launched by NASA in 2018, uses four CCD cameras to observe stars for light changes that are characteristic of exoplanet transits. Possible exoplanets are then given a TESS Object of Interest (TOI) designation, and need to be confirmed as exoplanets through follow-up observations from ground-based telescopes.

The TESS mission has identified over 7000 candidate exoplanets to-date, but only around 35% have been followed-up with ground-based observations [3]. Several publications use TESS data and ground-based observations to characterize planetary systems, for example a 2021 study verifying a four-planet system revolving around a sun-like star [4] or a 2024 study validating eight super-earth exoplanets across a range of host-stars [5]. In this study, we aim to perform ground-based observations on TOI 5356.01, which has not been previously verified, to assist in validating more TESS exoplanets.

In this paper, we present ground-based observations of TOI 5356.01 with the goal to verify the expected transit time, transit depth, and host-star of the exoplanet candidate and identify variations in our follow-up observations that do not align with data from TESS. TOI 5356.01 revolves around a main-sequence star twice the radius of our sun, in a period of around 3.19 days. It's predicted transit depth is 4.600ppt [6]. This information will be used to analyze the light curve of TOI 5356.01.

In **Section 2**, we present data from TESS and the George Mason University telescope. In **Section 3**, we present our analysis of the light curve for TOI 5356.01. In **Section 4**, we present our light curve results. In **Section 5**, we discuss our results. In **Section 6**, we present our conclusions and suggestions for further analysis.

2 Observations

In **Section 2.1** we present exoplanet and host-star properties of TOI 5356.01 from ExoFOP and other archival sources. In **Section 2.2**, we present a summary of the observational data collected using the George Mason University 0.8m telescope. In **Section 2.3** we present sector light curves gathered by the TESS mission.

2.1 Exoplanet and Host-Star Properties

The TESS Input Catalogue ID of TOI 5356.01 is TIC 467684543.01, which was first observed on February 28th, 2022. The object of interest in located at a RA/Dec of 04:03:51.52, +31:46:33.47 using the J2000 standard epoch, with a proper motion of RA/Dec (mas/yr) of -2.23893, 0.214764. Below are properties of TOI 5356.01 and its host-star retrieved from ExoFOP [6].

Table 1: TOI 5356.01 Predicted Exoplanet Properties, ExoFOP

Property	Value	Uncertainty
Period (days)	3.19487	±0.00051
Transit Depth (mmag)	5.0059	±0.0039
Transit Depth (ppt)	4.6000	±0.0036
Transit Duration (hrs)	3.786	±0.312
Radius (R⊕)	13.3231	±0.7736
Equilibrium Temperature (K)	1812	—

Table 2: TOI 5356.01 Predicted Host-Star Properties, ExoFOP

Property	Value	Uncertainty
Effective Temperature (K)	6577.37	±111.24
Surface Gravity (log(g))	3.9742	±0.0865
Radius (R⊙)	1.99656	±0.0976882
Mass (M⊙)	1.37	±0.21
Metallicity ([Fe/H])	-0.025	±0.049
Density (g/cm^3)	0.2427	±0.0578
Luminosity(L⊙)	6.7216	±0.4569

2.2 Observational Data

Data used in this study was collected from the Ritchey-Chretien 0.8 meter telescope at George Mason University, located at -77:18:19.24 longitude, +38:49:41.5 latitude, and an elevation of 148.72 meters above sea level.

TOI 5356.01 was observed on January 7th, 2023 from 18:05 EST to 3:00 EST on January 8th, 2023. The predicted time of transit ingress and egress were 18:34 EST and 22:22 EST on January 7th, 2023, respectively.

Data was captured using the R filter, which accepts light in the 550nm to 800nm wavelength [7]. Darks, flats, and sciences (also called "lights") were captured with the following parameters.

Table 3: Images Captured by GMU Observatory on 01-07-2023

Image Type	Number Taken	Exposure Time (s)
Dark	10	432
Dark	10	85
Flat	10	432
Science	311	85

2.3 TESS Light Curves

Previous TESS observations were used to validate our findings. Light curve data from 5 TESS Science Processing Operations Center (SPOC) Pipeline reports were retrieved from the MAST Archive [8]. All light curves were generated from observations conducted in the Optical wavelength. Metadata and analysis of TESS light curves is presented in **Section 4.2**.

3 Analysis

In **Section 3.1**, we present software used to analyze TOI 5356.01, notably AstroImageJ and EXOFAST1. In **Section 3.2**, we present methods used to generate light curves for TOI 5356.01 using AstroImageJ. In **Section 3.3**, we present analysis of TOI 5356.01 and its host-star (hereinafter "the target star") using EXOFAST1.

3.1 Analysis Tools

AstroImageJ (v5.3.4.02), developed by the University of Louisville, facilitates processing and analysis of astronomical image data in the .fits file format. AstroImageJ was used to conduct data reduction, plate-solving, multi-aperture photometry, and light curve generation. The ansvr plugin (v0.22), a local installation of Astrometry.net, provided plate-solving functionality to AstroImageJ.

EXOFAST1 (v1.7), developed by Eastman et al. in 2013, provides predicted exoplanet and host-star properties calculated from the characteristics of a detected transit. EXOFAST1 was used to generate a normalized light curve, predicted properties, and probability distributions. The web-based version of the software, hosted by the NASA Exoplanet Archive [9], was used to conduct analysis presented in **Section 3.3**.

3.2 AstroImageJ Analysis

AstroImageJ was used to generate a light curve from our observation of TOI 5356.01.

Observation images captured on the GMU telescope on January 7th, 2023 were downloaded and opened in AstroImageJ. Of the 311 science images, the first 214 were manually chosen to be used in further analysis. The 97 rejected images displayed overexposure to nearby light-sources or exhibited stars obscured by dense cloud-cover, as shown in **Figure 1**.

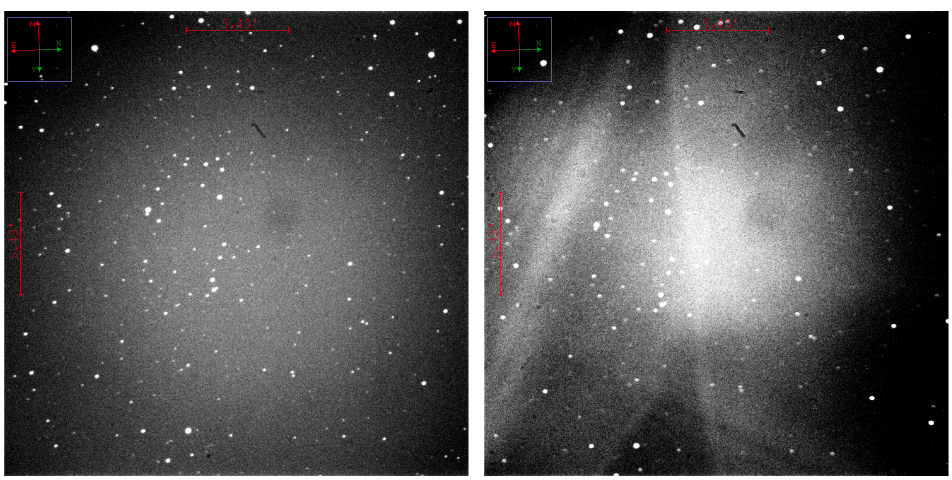


Figure 1: A good quality science (left) compared to a rejected science obscured by cloud cover (right).

Dark subtraction and flat division was conducted through AstroImageJ using the flat, dark, and science images captured. This removed variations caused by thermal noise and defects in camera pixels from the sciences. The resulting data-reduced sciences were plate-solved using ansvr, centering the images on the target star's RA/Dec of 04:03:51.52, +31:46:33.47. All plate-solves were successful, using parameters shown in **Figure 2**.

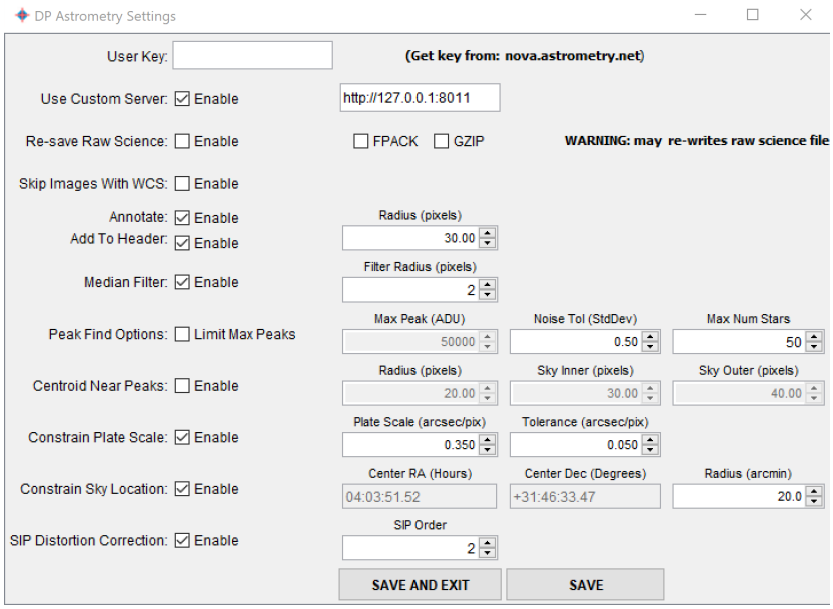


Figure 2: Plate-solving parameters selected in AstroImageJ.

To verify the results of plate-solving and ensure correct identification of the target star, an image of the target star, retrieved from MAST AstroView, was overlaid onto a plate-solved science using Krita, an image editing software. Alignment of surrounding stars, shown in **Figure 3**, allowed determination of the target star and validated the accuracy of the plate-solves.

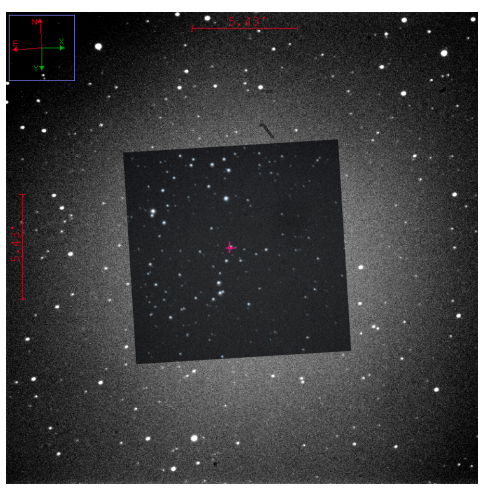


Figure 3: A smaller image of the target star from MAST aligned with stars on the larger science. A pink crosshair identifies the target star.

We then created a measurements table to produce a light curve of the target star. A seeing profile of the target star was taken using the Aperture Photometry Tool to determine the aperture and annulus radii of the star, shown in **Figure 4**. The aperture radius was 25.00px (9.00 arcseconds), with the inner and outer radii of the annulus being 43.00px and 65.00px respectively.

Multi-aperture photometry was then conducted to populate the measurements table with flux data of the target star, nearby stars, and reference stars. Parameters were chosen to match the specifications of the GMU telescope, shown in **Figure 5**.

A .radec file retrieved from the Gaia Archive contained 51 nearby stars within a 2.5 arcminute radius of the target star, of which 20 were manually deemed sufficiently distinct to be included in further analysis. Outside of the 2.5 arcminute radius, 31 stars in the science were identified as candidate reference stars. Apertures were placed around the selected stars as shown in **Figure 6**.

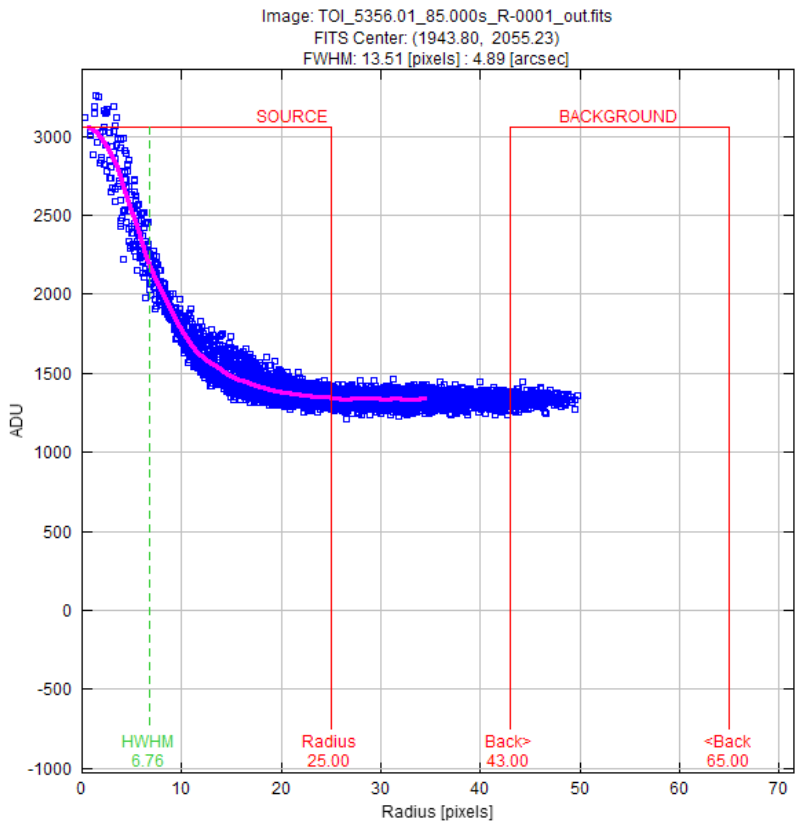


Figure 4: A seeing profile of TOI 5356.01 created using AstroImageJ.

To produce an accurate light curve, AstroImageJ was configured with data of host-star and exoplanet properties of TOI 5356.01. Predicted ingress and egress for the transit on January 7th, 2023 was obtained from the Transit Finder developed by Swarthmore College [10] using the associated time and location of the GMU observatory. The transit ingress and egress time in BJD_{TBD} was predicted to be 9952.4867 and 9952.6444 respectively, which was configured in AstroImageJ by removing values before the decimal (thus, 0.4867 and 0.6444 respectively). The exoplanet's period of 3.19 days was configured along with the its host-star radius of 1.997 R⊙. Based on the host-star radius, AstroImageJ automatically predicted other host-star properties, listed in **Table 4**, which do not all agree with data collected from ExoFOP, listed in **Table 2**.

Table 4: TOI 5356.01 Predicted Host-Star Properties, AstroImageJ

Property	**Value**
Stellar Classification	A5V
Effective Temperature (K)	8719
J-K Color Index	0.046
Mass (M⊙)	2.381

The data was then adjusted for quadratic limb darkening, with data obtained from Ohio State University [11]. Values for host-star effective temperature, metallicity, surface gravity, and telescope imaging band were entered as 6577.37K, -0.025[Fe/H], 3.9742log(g), and R band, respectively. This produced a Linear LD u1 of 0.25795258 and Quadratic LD u2 of 0.32711273.

The final light curve graph was created by adjusting the scale, position, and labels of data visualizations and axes, and adjusting the reference stars and detrending parameters to produce optimal results, presented in **Section 4.1**.

Finally, a near-eclipsing binary (NEB) check was run to search for possible NEBs that could have produced light-curves. The 20 Gaia stars within a 2.5 arcminute radius of the target star, and the target star itself were checked and a graph of root mean square (RMS) vs. Δmagnitude (Δmag),

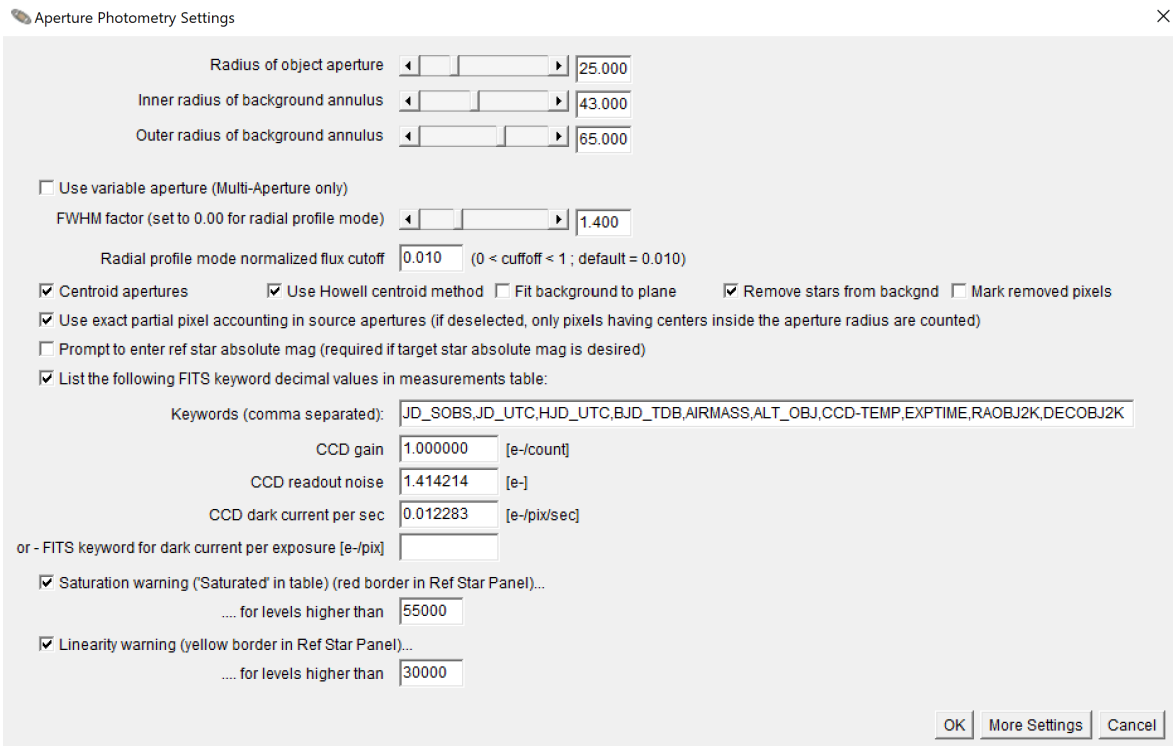


Figure 5: Multi-aperture photometry parameters selected in AstroImageJ.

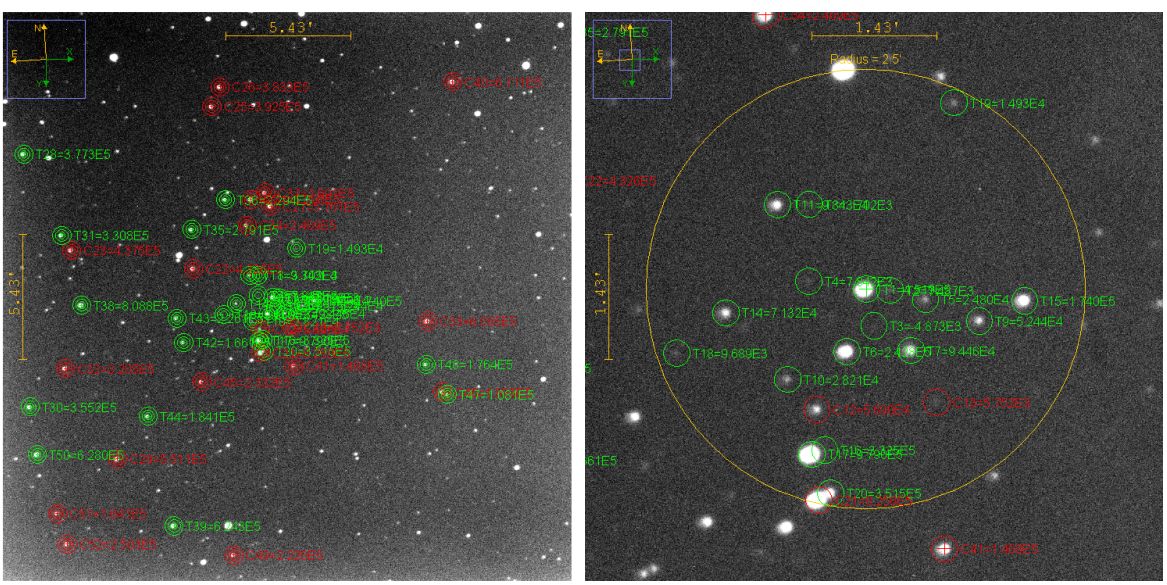


Figure 6: A science containing all 52 placed apertures (left) and a close up of visible Gaia stars within a 2.5 arcminute radius of the target star (right).

Figure 7, was created. Unfortunately, no stars lie below the green "Cleared Boundary" or pink "Likely Cleared Boundary" lines, leaving the possibility for the apparent transit to be caused by a NEB. Stars T16 and T20 are outliers and do not follow the curved distribution of the other stars, and thus cannot be used as references (which are designated C). However, the majority of stars follow an organized distribution which is evidence to suggest that any possible NEB must be identified through alternative analysis as there are no significant abnormalities within nearby stars regarding RMS vs. Δmag. TOI 5356.01 could be a NEB, however the RMS vs. Δmag cannot provide conclusive evidence. Individual NEB check graphs are omitted for concision.

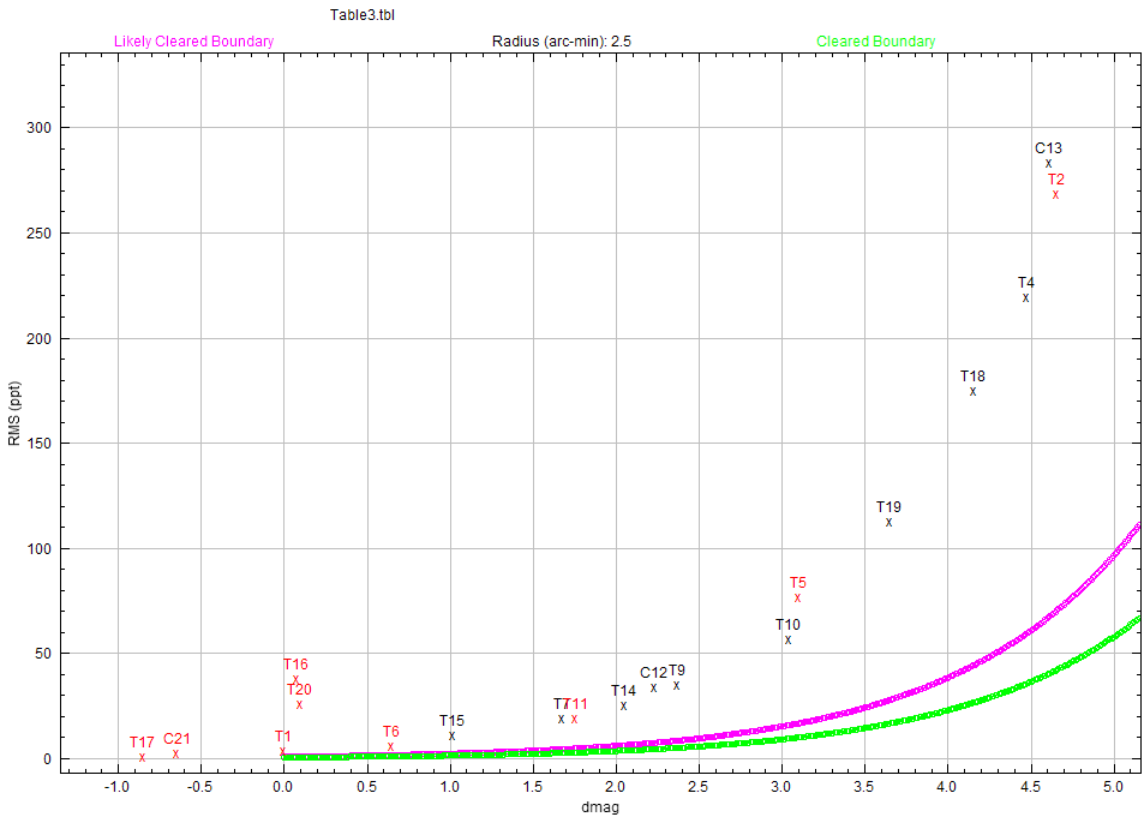


Figure 7: An RMS vs. Δmag graph checking for NEBs.

3.3 EXOFAST Analysis

EXOFAST1 was used to find properties of TOI 5356.01 and its host-star through χ^2 and Markov-chain Monte Carlo (MCMC) fitting.

A transit file was prepared for EXOFAST1 using the measurement file generated in AstroImageJ by filtering for BJD_{TDB}, relative flux T1, relative flux error T1, sky/pixel T1, and width T1 data columns. The observation band was set to R.

Priors and prior widths for stellar and planetary properties were produced from AstroImageJ predictions and ExoFOP data, shown in **Table 5**.

A χ^2 fitting run was configured with a minimum and maximum period of 3.19436 and 3.19538 days respectively. Our observations did not record radial velocity (RV) data, and TOI 5356.01 has no previous radial velocity observations. Thus, the "Force Circular Orbit" option was checked as recommended for a fitting using purely transit data. This run produced a .tar archive which contained predicted values for host-star, exoplanet, transit, and secondary eclipse properties. Fitting accuracy was presented through χ^2 coefficients.

A MCMC fitting run was also configured with the same parameters, producing probability distributions and covariance parameter plots for predicted properties.

Table 5: Priors and Prior Widths EXOFAST1 Runs

Property	**Prior**	**Prior Width**
Transit Midpoint (days)	2459952.565	0.015
R_p to R_* Ratio	0.06118	—
Orbital Incliation (deg)	89.9999	15.0
a to R_* Ratio	8.2772	7.0
Baseline Flux	0.0605	0.0121
Linear LD u1	0.25795258	—
Quadratic LD u2	0.32711273	—
Stellar Surface Gravity (log(g))	3.9742	0.0865
Stellar Effective Temperature (K)	6577.37	111.24
Metallicity ([Fe/H])	-0.025	0.049
Orbital Period (days)	3.19487	0.00051

4 Results

In **Section 4.1**, we present the target star light curve generated by AstroImageJ. In **Section 4.2**, we present a comparison between our produced light curve and previous light curves produced by the TESS mission. In **Section 4.3**, we present parameter predictions of TOI 5356.01 and its host-star from EXOFAST1.

4.1 AstroImageJ Results

Upon completion of multi-aperture photometry, AstroImageJ produced a preliminary light curve based on default selections. We then adjusted detrending settings and reference stars with the goal of reducing the root mean square (RMS) scattering of the normalized flux data.

The final light curve was produced using 21 reference stars, 18 of which were not Gaia stars within 2.5 arcminutes of the target star. Detrending parameters chosen were sky/pixel T1 and width T1, which significantly reduced RMS. The fit and normalize region was kept similar to the predicted transit time in relative BJD_{TDB}, with ingress and egress at 0.5000 and 0.6300 respectively.

We present the finalized light curve in **Figure 8**, which incorporates several plots listed below.

1. **rel_flux_T1 Normalized:** Normalized flux data of the target star, without detrending.
2. **rel_flux_T1 Detrended:** Flux data detrended for sky/pixel T1 and width T1. The line through the middle graphs the transit model.
3. **rel_flux_T1 Residuals:** Residuals of transit model fitting.
4. **rel_flux_C24:** Normalized flux data of a reference star, no transit is visible as expected.
5. **Sky/Pixel_T1:** Normalized flux data of the sky.
6. **Width_T1:** Observed width of the target star over time.
7. **AIRMASS:** Thickness of the atmosphere in observational direction over time.
8. **tot_C_cnts:** Total counts for all stars over time.
9. **X(FITS)_T1:** X coordinate of the target star over time.
10. **Y(FITS)_T1:** Y coordinate of the target star over time.

The observed depth of transit was 4.55ppt (parts-per-thousand). The RMS value of the detrended data is 4.36ppt with a Bayesian information criterion (BIC) of 275.8. The χ^2/dof (degrees of freedom) fit value of the transit model is 1.15. A significant decrease in flux can be seen in the normalized flux with and without detrending, during the predicted time of transit.

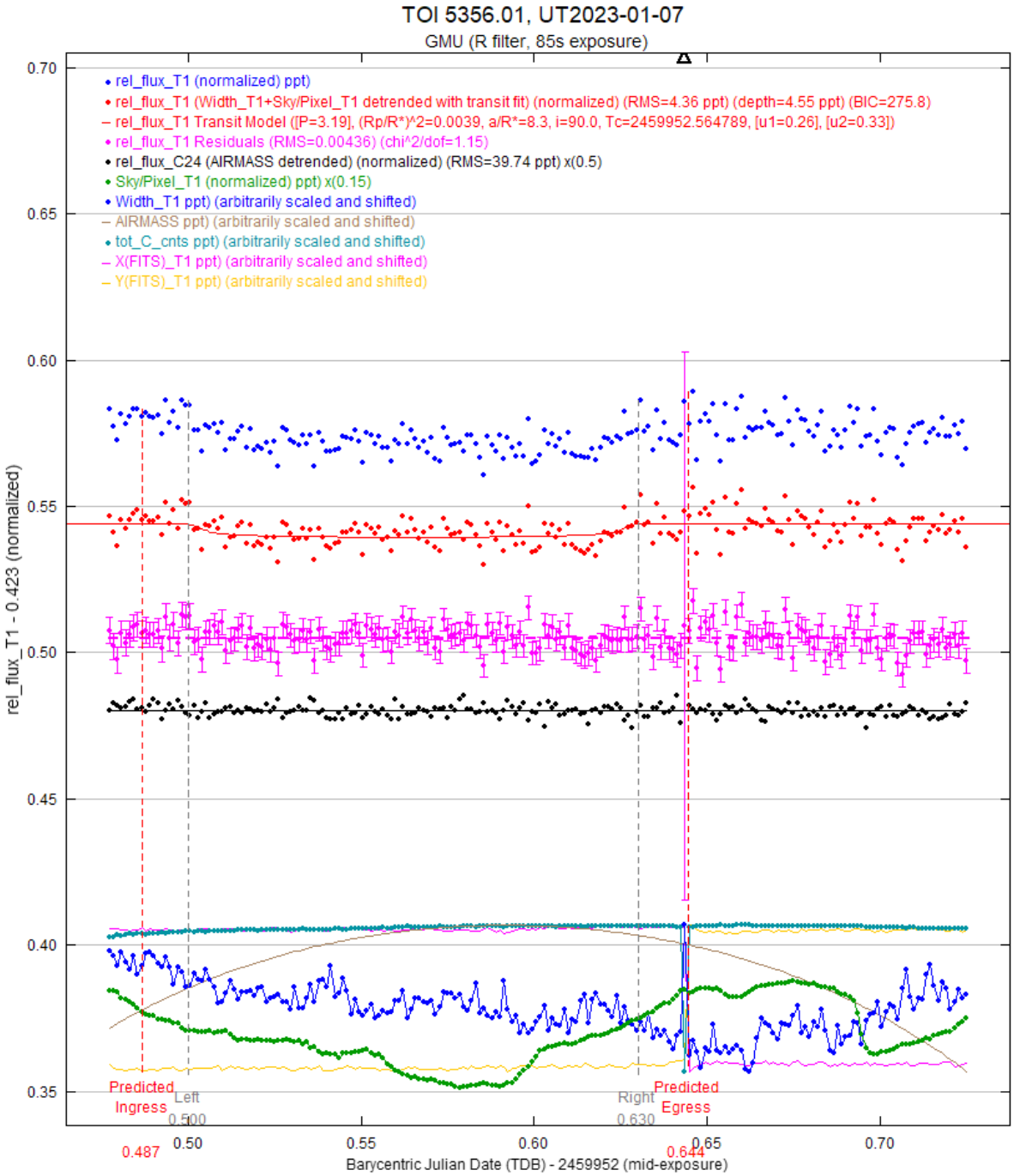


Figure 8: A final light curve of TOI 5356.01.

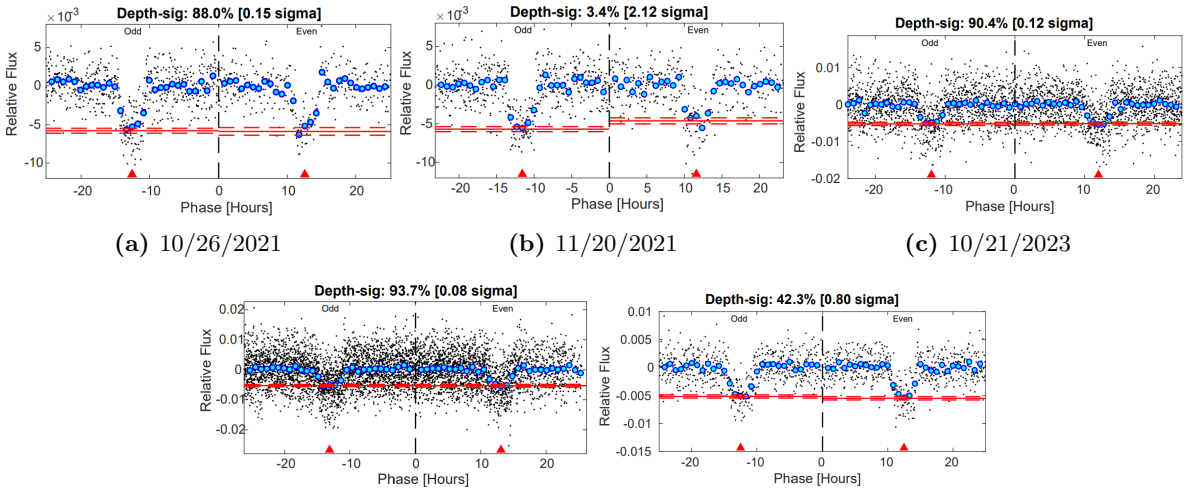
4.2 TESS Light Curve Comparison

Data for 5 light curves of TOI 5356.01 collected from TESS is listed in **Table 6**. Observations compiled on October 21st and November 15th in 2023 suggest the exoplanet's period is around 6.390 days, however this is simply a result of TESS data gaps that aligned with the transit time, causing the predicted period to be multiplied by 2. Some transits are still visible in the raw light curve data, although not recorded after the period was doubled.

Table 6: Light Curve Data of TESS Observations on TOI 5356.01

Date	Total Transits	Period (days)	Avg. Depth (ppt)
10/26/2021	6	3.195	5.7618
11/20/2021	7	3.194	5.2909
10/21/2023	4	6.389	5.2240
11/15/2023	8	3.193	5.2964
12/17/2023	8	6.390	5.2785

An even-odd check was performed as another test for NEBs. The orbital properties of an NEB create differences in flux changes between even and odd numbered transits. Relative flux vs. phase graphs were obtained from TESS SPOC, shown in **Figure 9**. The observations compiled on 10/21/2023 and 12/17/2023 were utilized as expected variations between transit depths (the even-odd checks for these observations are conducted on every other transit, essential making the check compare same-numbered transits). We observe small variations in transit depth, 0.12 and 0.80 standard deviations, respectively, as expected from same-numbered transits. The 3 other observations have transit depth variations of 0.15, 2.12, and 0.08 standard deviations between odd and even transits. Disregarding the 2.12σ outlier, these variations are reasonably similar to those of the same-numbered transits, suggesting that TOI 5356.01 is not a NEB. However, the small sample size of light curves prevents conclusive determination against an NEB classification.



(a) 10/26/2021 **(b)** 11/20/2021 **(c)** 10/21/2023

(d) 11/15/2023 **(e)** 12/17/2023

Figure 9: Even-Odd check graphs of light curve transits.

The transit time of TOI 5356.01 in the TESS light curves was around 4 hours. The observed transit time was around 3 hours in length, and with an ingress/egress uncertainty of 1 hour and 39 minutes, our ground-based observation transit time is with in the margin of error compared to the TESS observed transit times.

4.3 EXOFAST Results

EXOFAST1 produced a detrended, normalized light curve using submitted transit data, shown in **Figure 10**.

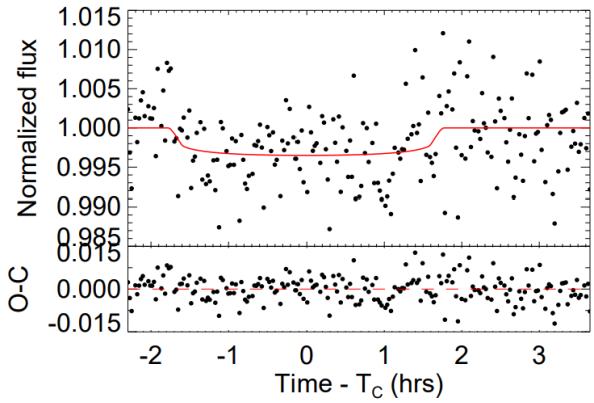


Figure 10: An EXOFAST1 generated light curve of TOI 5356.01, the lower graph plots errors.

The χ^2 and MCMC fitting runs from EXOFAST1 returned stellar, planetary, and transit properties, shown and compared in **Tables 7, 8, and 9**. Generated probability distributions and covariance plots are omitted for concision. The MCMC fitting seems to better match the predicted data from ExoFOP for more properties, however all three sources provide remarkably similar values. The χ^2/dof value of the transit fit was 1.216, and the χ^2/dof value of the combined fit was 0.997.

Table 7: TOI 5356.01 Predicted Host-Star Properties, EXOFAST

Property	**ExoFOP**	**EXOFAST χ^2**	**EXOFAST MCMC**
Mass (M$\odot$)	1.37	1.474936	1.454449
Radius (R$\odot$)	1.99656	2.055320	1.966212
Luminosity (L$\odot$)	6.721552	7.100371	6.503798
Density (g/cm^3)	0.2427	0.239757	0.269499
Surface Gravity (log(g))	3.97422	3.981132	4.012361
Effective Temperature (K)	6577.37	6577.050049	6575.711741
Metallicity ([Fe/H])	-0.025	-0.025079	-0.025565

Table 8: TOI 5356.01 Predicted Exoplanet Properties, EXOFAST

Property	**ExoFOP**	**EXOFAST χ^2**	**EXOFAST MCMC**
Period (days)	3.1948695	3.194870	3.194872
Semi-Major Axis (AU)	—	0.048313	0.048088
Radius (R$\oplus$)	13.3231	12.293996	12.617247
Equilibrium Temperature (K)	1812	2068.289145	2028.608624

Table 9: TOI 5356.01 Predicted Transit Properties, EXOFAST

Property	**ExoFOP**	**EXOFAST χ^2**	**EXOFAST MCMC**
Linear LD u1	0.25795258	0.258654	0.253503
Quadratic LD u2	0.32711273	0.328388	0.324823
Transit Depth (ppt)	4.600	3.008	3.695
Transit Duration (days)	0.15775	0.213740	0.160445

5 Discussion

We now interpret our observations and analysis on TOI 5356.01, to determine if it is a valid exoplanet.

Statistical interpretation of our results suggest that TOI 5356.01 is likely an exoplanet. Observation images were taken in decent conditions for accurate transit data to be collected. The observed depth of transit was 4.55ppt, very similar to the 4.60ppt of the predicted transit, and similar to the transit depths recorded by TESS light curves, shown in **Table 6**. The model RMS of 4.36ppt and χ^2 value of 1.15 describe a relatively closely clustered and well-fitted transit model to the observed data. Our data is consistent with previous findings and rather precise, which supports the validation of TOI 5356.01 as an exoplanet.

A transit is apparent upon visual examination of the normalized and detrended light curves, shown in **Figure 8**, and the decrease in flux from the target star is contained in the predicted egress and ingress times within the margin of error. The data may have been influenced by external environmental factors, however careful detrending and reference star selection removes some of this perturbation. Two NEB checks were performed, see **Sections 3.2 and 4.2**, which yielded inconclusive results but provided evidence to suggest that the observational data did not show characteristics of a NEB. Our data is indicative of a transit and provides reasoning against a false-positive.

TOI 5356.01's characteristics suggest that it is a hot Jupiter. Its predicted period is around 3.19 days, consistent with hot Jupiters, which usually have periods less than 10 days [12]. The equilibrium temperature of 1800-2000K, short semi-major axis of 0.048AU and planetary radius around 11-13 times that of earth suggest that TOI 5356.01 is a hot, Jupiter sized world, orbiting close to its host-star. The observed transit depth of 4.55ppt corresponds to a change in host-star flux of 0.455%. Previous studies suggest that a transit of a Jupiter-sized planet over a Sun-like star yield changes in flux of 1% [13]. Our exoplanet is slightly larger than Jupiter and its host-star is twice the radius of the Sun, which indicates an expected flux change of around 0.30-0.35%, as corresponding to the EXOFAST predicted transit depths of 3.008ppt and 3.695ppt. This is reasonably close to the observed change in flux, supporting the classification of TOI 5356.01 as a hot Jupiter.

6 Conclusions and Future Work

Based on our ground-based follow-up observations and comparisons with available data, we conclude that TOI 5356.01 is most likely an exoplanet. A RMS vs. Δmag and even-odd check for NEBs were inconclusive but provided strong indications that TOI 5356.01 did not interact with a NEB system. Available data from ExoFOP, supported by predictions made using EXOFAST1, suggest that the exoplanet candidate fits the description of a hot Jupiter, with MCMC predicted equilibrium temperatures of 2028.6K and a radius of 12.62 earths. Our conclusions suggest that TOI 5356.01 is a good candidate for further research and statistical analysis. An important next step would be to consider more rigorous tests for false-positives or NEBs, and observations of TOI 5356.01's radial velocity, which would provide further evidence toward its identification as an exoplanet. Software like VESPA could be used for false-positive analysis, although its developers have suggested improved solutions [14]. Further research might focus on the planet's environment, composition, and structure, which can be used as a basis for exploration on TOI 5356.01's ability to support life. We conclude that TOI 5356.01 holds potential for future study.

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