Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest TOI 5516.01

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Abstract

The Transiting Exoplanet Survey Satellite (TESS) is designed to discover thousands of exoplanets in orbit around the brightest dwarf stars in the sky. In order to do this, along with discovering new exoplanet candidates, ground-based observations are needed to confirm that the candidates, the TESS Objects of Interest (TOIs), are planets. This paper presents the results of a follow-up ground based observation conducted on the candidate exoplanet TOI 5516.01. The goal of this investigation was to determine if there was a transit detected for TOI 5516.01 and if it occurred near the expected star, and at the expected time, with the expected duration and orbital depth. Employing data from the Transiting Exoplanet Survey Satellite (TESS) and ground-based observations from George Mason University's 0.8m telescope, AstroImageJ was used to carry out multiple processes including data-reduction, plate-solving, aperture photometry, multi-aperture photometry, and NEB analysis in order to allow for light curve generation. Our observations and data resulted in an inconclusive outcome, where we are unable to precisely conclude whether a transit was detected or not.

Keywords: TESS, exoplanet, ground-based observation, TOIs, AstroImageJ, transit, light curve generation

Section 1

Introduction

For millennia, we have wondered whether other stars have planets, and whether those planets might harbor life. Within the last few decades, it has become possible to make progress on these timeless questions. Exoplanetary science — the study of planets around other stars — is one of the newest and most rapidly growing branches of astrophysics[1].

Until the 1990s, the only planets we knew existed were in orbit around the sun. Since 1992, astronomers have discovered thousands of exoplanets: worlds in orbit around other stars. Based on the data we have, researchers think there could be hundreds of billions of planets in the Milky Way alone. Current exoplanet research takes many forms: developing methods to find new worlds, looking for signs of certain molecules in their atmospheres, and studying newborn planets around young Stars. Astronomers are working on the next generation of telescopes to find Earth-like worlds and possibly signs that life might exist on other planets[2].

Transiting exoplanets offer opportunities to explore the compositions, atmospheres, and orbital dynamics of planets beyond the solar system. The Transiting Exoplanet Survey Satellite (TESS) is a NASA-sponsored Explorer mission that will monitor several hundred thousand Sun-like and smaller stars for transiting planets (Ricker et al. 2015). The brightest dwarf stars in the sky are the highest priority for TESS because they facilitate follow-up measurements of the planet masses and atmospheres.

Oftentimes, early work leaves some questions unanswered or opens new questions. Therefore, in this research paper, we present a comprehensive analysis of the image data associated with TOI 5516.01 from the George Mason Observatory's 0.8m telescope. Through AstroImageJ (AIJ), we went through processes such as data-reduction, plate-solving, aperture photometry, multi-aperture photometry, and NEB analysis in order to allow for light curve generation. Our findings shed light on the nature of TOI 5516.01 and its role in expanding our knowledge of a variety of exoplanets.

In this paper, we present follow-up observations of TOI 5516.01, also known as TIC 70678449.01. As measured by TESS, the candidate exoplanet's transit midpoint is approximately 2459574.485 BJD, the orbital period is approximately 4.38 days, and the transit duration is

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[1] "Exoplanets | MIT Kavli Institute." 2018. MIT Kavli Institute | Institute for Astrophysics and Space Research. August 13, 2018. https://space.mit.edu/research/exoplanets/.

[2] "Exoplanets | Center for Astrophysics." n.d. Www.cfa.harvard.edu. https://www.cfa.harvard.edu/research/topic/exoplanets.

approximately 2.86 hours.[3] Our objective is to investigate whether or not the transit occurs on the expected star at the expected time, with the expected duration and depth.

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 5516.01 and our ground-based light curve analysis. In section 4, we present our light curve results. In Section 5, we discuss our results and in section 6, we present our conclusions and future work.

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[3] "TOI-5516 | NASA Exoplanet Archive." 2022. Caltech.edu. 2022. https://exoplanetarchive.ipac.caltech.edu/overview/TOI-5516.01#planet_TOI-5516-01_collapsible.

Section 2

Observations

In section 2.1, we present the TESS object of interest TOI 5516.01 and its exoplanet candidate properties along with its host star properties from the TESS input catalog and in section 2.2, we present a summary of the observational data for TOI 5516.01 collected with the George Mason University 0.8m telescope.

Section-2.1: TESS Observational Data

The TESS Input Catalog ID of our object of interest TOI 5516.01 is TIC 70678429. The data for TOI 5516.01 was created in 2022. The RA coordinate of TOI 5516.01 is 10:23:21.20s and the DEC coordinate of TOI 5516.01 is +13:28:20.03s. As measured by TESS, the candidate exoplanet's transit midpoint is approximately 2459574.485 BJD, the orbital period is approximately 4.38 days, and the transit duration is approximately 2.86 hours. Additionally, the candidate exoplanet's transit depth is approximately 3.9 ppt, its radius is approximately 12.34 R_Earth, and its insulation is approximately 448.118 Earth fluxes. Finally, its average temperature is approximately 1281 K. Additionally, as measured by TESS, the distance between Earth and the host star is 857.001 pc. The stellar effective temperature is approximately 6077 K, the stellar log(g) is approximately 3.882 cm/s^2, and the stellar radius is approximately 2.025 R_Sun.
[4]

Section-2.2: GMU Telescope Observations

In this study, we used the George Mason University 0.8m telescope in Virginia to observe a total of 167 sciences, each with an exposure time of 75s, starting from 23:55 UTC on Sunday, February 25, 2024 to 10:48 UTC on Monday, February 26, 2024. The GMU 0.8m telescope uses an R filter. As stated above in Section 2.1, the RA coordinate of TOI 5516.01 is 10:23:21.20s and the DEC coordinate of TOI 5516.01 is +13:28:20.03s.[5]

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[4] "TOI-5516 | NASA Exoplanet Archive." 2022. Caltech.edu. 2022. https://exoplanetarchive.ipac.caltech.edu/overview/TOI-5516.01#planet_TOI-5516-01_collapsible.

[5] "TOI-5516 | NASA Exoplanet Archive." 2022. Caltech.edu. 2022. https://exoplanetarchive.ipac.caltech.edu/overview/TOI-5516.01#planet_TOI-5516-01_collapsible.

Section 3

Analysis

In section 3, we present our process of generating a light curve for TOI 5516.01 using AstroImageJ. The astronomical software AstroImageJ allows astronomers to display images captured from telescopes. It facilitates processes such as data-reduction, plate-solving, aperture photometry, multi-aperture photometry, and NEB analysis in order to allow light curve generation. In this study, we used AstroImageJ and these above-mentioned processes and tools to analyze the candidate exoplanet associated with TOI 5516.01.

AstroImageJ (AIJ) was utilized for data reduction and these data-reduced images underwent plate-solving to establish precise World Coordinate System (WCS) coordinates and later, multi-aperture photometry and NEB analysis to facilitate the process of light-curve generation.

In order to prepare for data-reduction, we downloaded and organized the 167 images captured by the GMU telescope on February 25th, 2024 into sciences, flats, science darks and flat darks. The telescope focused on our object of interest (target) TOI 5516.01, which has RA and Dec coordinates of 10:23:21.20s and +13:28:20.03s, respectively.[6] We also undertook a visual inspection of the sciences in an effort to identify defects such as streaking or target misalignment as a result of telescope corrections. As a result of considerable light pollution on the night of the data collection, certain observations were affected. However, the effect of this pollution on the images was alleviated through background subtraction during the data reduction process. Data reduction is important as it removes the instrumental signature and contaminant sources and thus, saves space, improves efficiency, and makes it significantly easier and faster to interpret and plate-solve images.
[7]

Secondly, we utilized Astronomy.net and AstroImageJ for plate solving, which included dark subtraction and flat division. We also created a finding chart using Swarthmore's annotated celestial maps generator to identify the TESS candidate Object of Interest in the field of view.

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[6] "TOI-5516 | NASA Exoplanet Archive." 2022. Caltech.edu. 2022. https://exoplanetarchive.ipac.caltech.edu/overview/TOI-5516.01#planet_TOI-5516-01_collapsible.

[7] Freudling, W., M. Romaniello, D. M. Bramich, P. Ballester, V. Forchi, C. E. García-Dabló, S. Moehler, and M. J. Neeser. 2013. "Automated Data Reduction Workflows for Astronomy." *Astronomy & Astrophysics* 559 (November): A96. https://doi.org/10.1051/0004-6361/201322494.

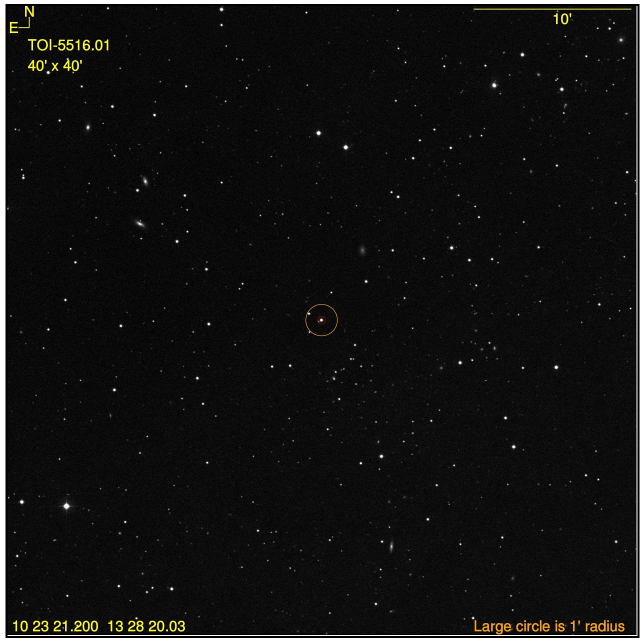


Figure- 1: *Finding chart of TOI 5516.01*

By utilizing the “Plugins” tool in AIJ, we generated a seeing profile to identify the target’s radius (aperture size), as well as inner and outer radii (annulus sizes). We achieved a photometry radius of 27, an inner annulus radius of 47, and an outer annulus radius of 70 pixels.

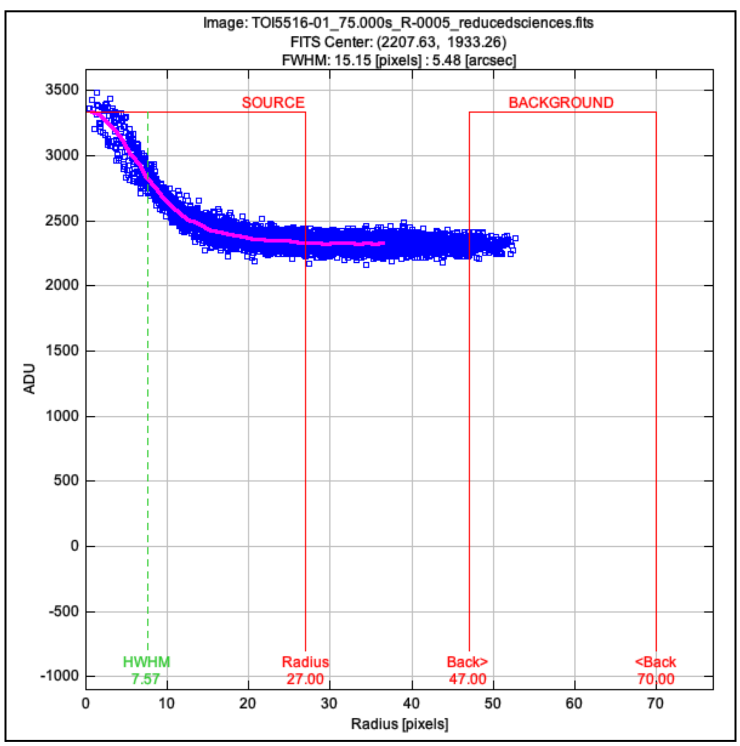


Figure- 2: *Seeing profile of TOI 5516.01*

The target's radius (aperture size) as well as inner and outer radii (annulus sizes) were entered into the Aperture Photometry Tool settings to place on the target and reference stars. Following this, we applied the differential photometry technique using the multi-aperture photometry tool in AstroImageJ. We conducted this by comparing the target star's brightness with that of several reference stars within the same Field of View (FOV) to remove any systematic variations. These reference stars were chosen to closely match the size and brightness of the target star - a vital step to ensure accurate normalization and reduction of systematic errors.

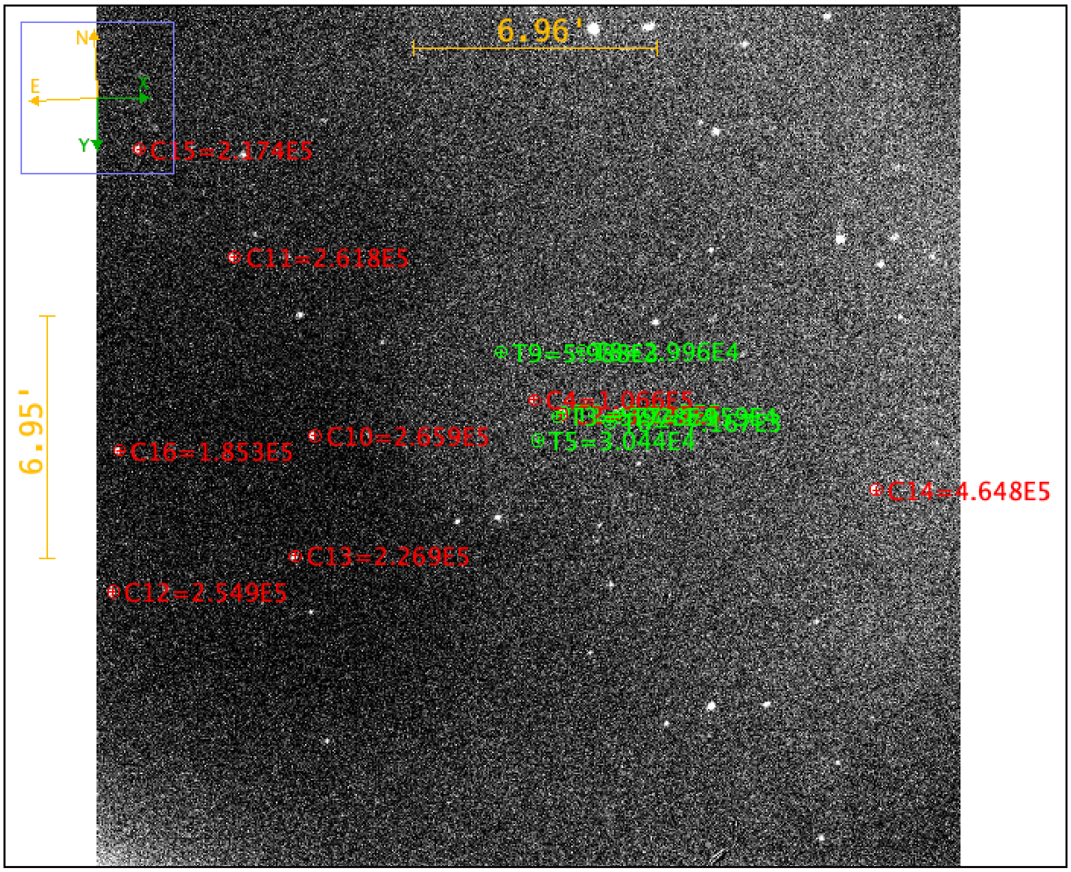


Figure- 3: *Field Image with Apertures For Reference Stars of TOI 5516.01*

From aperture photometry, a measurement table was generated and into it, we input values for Linear LD u1 and Quad LD u2, metallicity, and effective temperature for quadratic limb darkening. It also included a dataset that contained parameters like Barycentric Julian Date (TDB), sky and pixel information, width, air mass, total counts and image coordinates. In order to generate the light curve, we reviewed each reference star and discarded those that caused significant scattering or variation in the light curve.

Furthermore, we performed an NEB analysis and a DMag-RMS plot was generated to identify and reduce outliers, which displayed variations in magnitude with respect to predicted ingress and egress times. If any outliers were detected, they were excluded from the analysis by adjusting the Multi-plot Reference Star Settings accordingly.

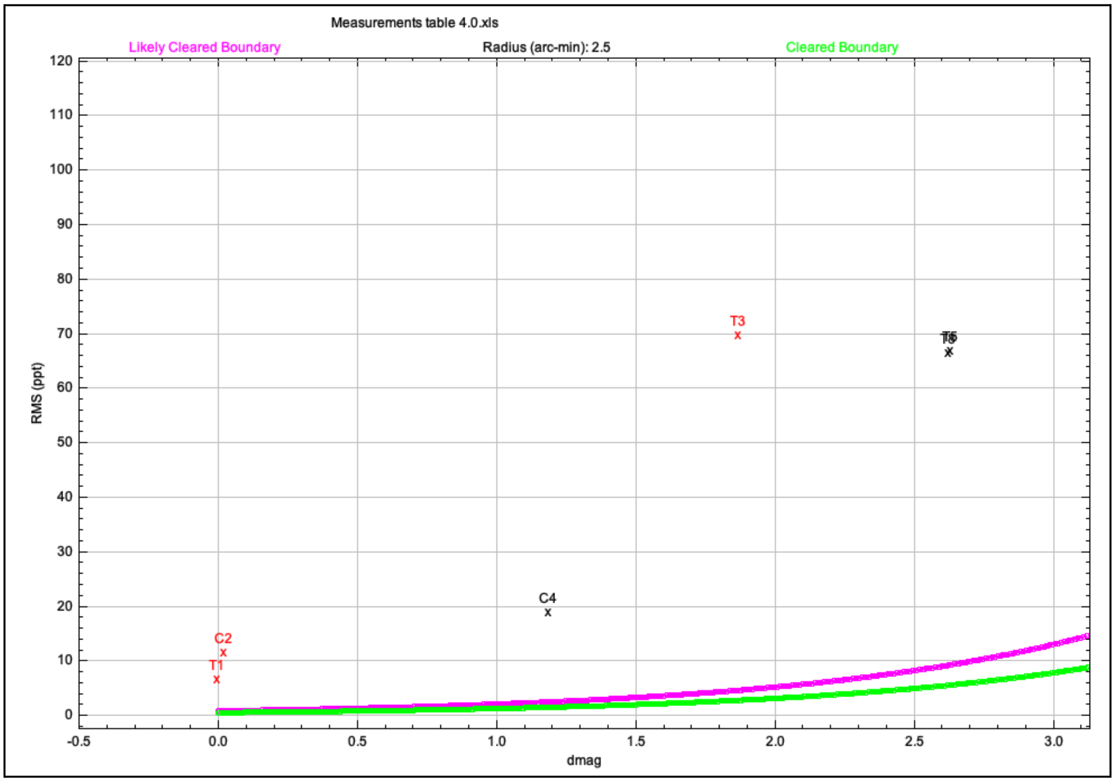
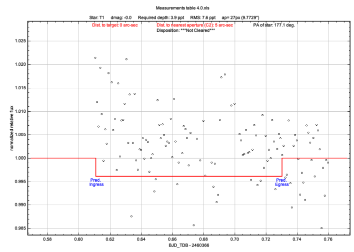
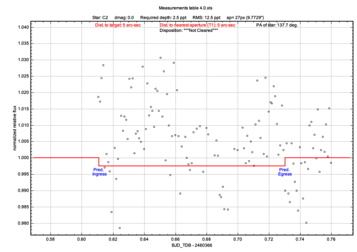


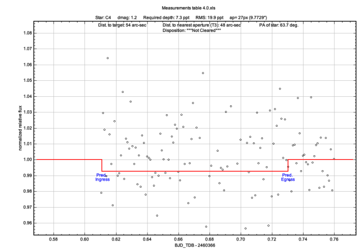
Figure-4 : *Delta Magnitude (Dmag) vs. RMS Plot*



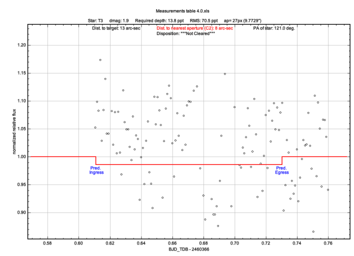
(a)



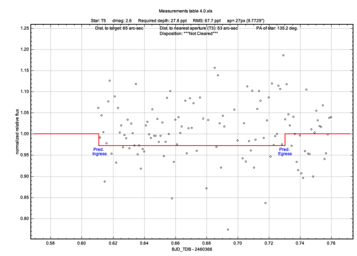
(b)



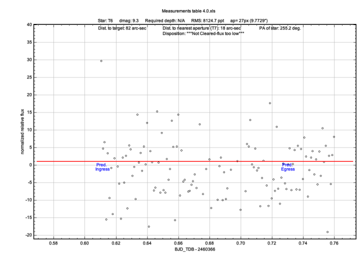
(c)



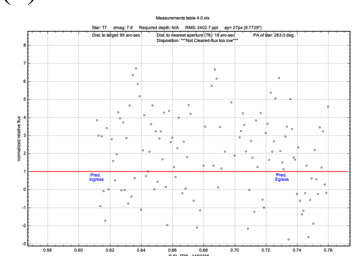
(d)



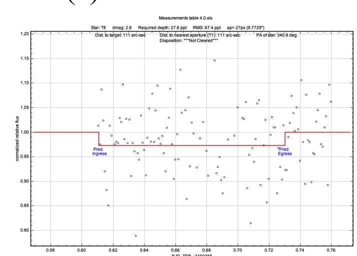
(e)



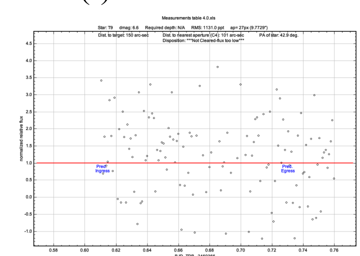
(f)



(g)



(h)



(i)

Figure-5*: Near Eclipsing Binary (NEB) plots, where (a) corresponds to T1, (b) corresponds to C2, (c) corresponds to T3, (d) corresponds to C4, (e) corresponds to T5, (f) corresponds to T6, (g) corresponds to T7, (h) corresponds to T8, (i) corresponds to T9*

Once we completed the prior steps, we were able to plot the light curve for TOI 5516.01 and look for potential dips in the light curve that would indicate an exoplanet transit.

Section 4

Results

In section 4, we are presented with the resulting light curve plot, produced using the R filter and which illustrates the flux variations of the target transit TOI 5516.01 over the observation period on February 25, 2024. The x-axis represents the Barycentric Julian Date (TDB), the y-axis indicates the relative flux (rel_flux) of the star and the markers denote the predicted ingress and egress times. The chi^2/dof we generated was 0.733, which is also not statistically significant at the significance level of 0.05.

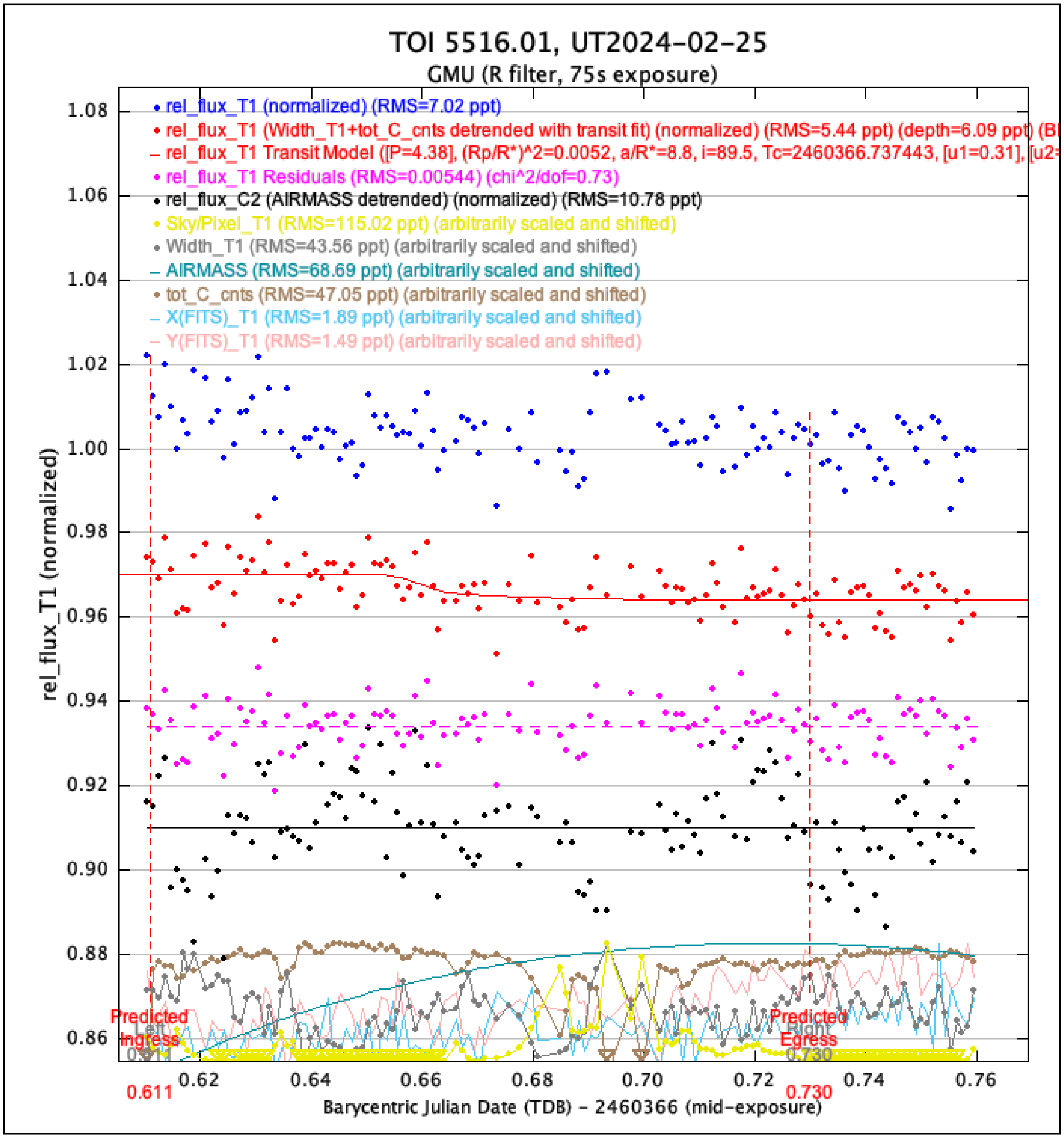


Figure-6: *Light curve plot of TESS Object of Interest (TOI) 5516.01*

Section 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.

Section-5.1:

Looking at the results from the NEB check, the stars cannot be ruled out as NEBs because of their high RMS values. Looking at the light curve generated, the measured depth of the transit model is about 6 ppt, while the RMS is 5.4 ppt. Since the measured depth is not significantly higher than the noise of the data (RMS), the transit AstroImageJ is detecting is not very statistically significant. At the same time, both the measured depth of the transit model and the RMS is higher than the predicted 3.9 ppt transit depth. This means that a 3.9 ppt transit could very well have been observed, but we lack the precision to actually see it. We are unable to verify the likelihood of the exoplanet candidate existing as we do not have the precision to say one way or the other. Thus, our observations and data resulted in an inconclusive outcome.

Section-5.2:

Hot Jupiters typically have a temperature of ~2700 K[8]. Our planet has a temperature of ~1281 K, which is significantly lower than the temperature of a hot Jupiter. The temperature of the TOI 5516.01 exoplanet does not indicate that it is potentially a hot Jupiter. On the other hand, hot Jupiters typically have orbital periods smaller than 10 days and our exoplanet has an orbital period ~1.389 days, which is significantly smaller than 10 days. Thus, we cannot say for certain whether our exoplanet candidate is a hot Jupiter.

Section 6

Conclusions And Future Work

From our results and discussion, we cannot determine whether TOI 5516.01 is an actual exoplanet. Our data and observations led us to an inconclusive result. A transit could very well have been observed, but we lack the precision to actually see it and thus, cannot determine whether it is likely or not that a transit occurred. We are unable to verify the likelihood of the exoplanet candidate existing as we do not have the precision to say one way or the other. We were also unable to determine if the exoplanet candidate fit the profile of a Hot Jupiter as it

[8] Wang, Ji, Debra A. Fischer, Elliott P. Horch, and Xu Huang. 2015. "ON the OCCURRENCE RATE of HOT JUPITERS in DIFFERENT STELLAR ENVIRONMENTS." *The Astrophysical Journal* 799 (2): 229. https://doi.org/10.1088/0004-637x/799/2/229.

carried temperatures much lower than those that hot Jupiters are usually characterized by, but also had an orbital period which was less than 10 days, similar to hot Jupiters. TOI 5516.01 shows good potential for further research.

All in all, we believe this exoplanet candidate is open to examination and analysis by interested parties in the coming future. Works can expand upon this research by conducting more detailed statistical analyses such as false positive analysis, MCMC analysis, radial velocity analysis etc on the target transit TOI 5516.01 using systems like ExoFASTv2 and Vespa to find more conclusive results and determine whether our exoplanet candidate exists.

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