Ground-based light curve follow-up validation observations of TESS object of interest TOI 5356.01

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Abstract:

Context: The current definition of an exoplanet is changing the more we learn about them. Several exoplanet detection missions have been launched over the years since the first one was discovered, each using different detection methods with the most successful one being the transit method. Detecting exoplanets does not always mean they are confirmed, and they must be checked and reviewed to determine their existence.

Aims: The goal of this paper is to present the results of a follow up observation of the exoplanet candidate: 5356.01. The observation and conclusion help to build upon our definition of an exoplanet and how they form.

Methods: We used python to enhance a TESS light curve, and AIJ (Astro Image J) to perform a ground-based light curve analysis. Data for the analysis was recorded at the George Mason University Observatory.

Results: Based on the light curve and NEB check of the target star, it can be concluded that it is a promising exoplanet candidate. However, due to the inconclusiveness of the RMS and dmag plot, it cannot be ruled out that it is a false positive caused by an NEB. Further observations are needed with a more capable telescope.

Keywords: TESS, exoplanet, Astro Image J, transit, TOI-5356.01, NEB.

1. Introduction:

The current accepted definition of an exoplanet is defined in three statements worked on by the IAU (International Astronomical Union). The three statements are as follows:

1. "Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars, brown dwarfs or stellar remnants and that have a mass ratio with the central object below the L_4 / L_5 instability ($M / M_{central} < 2 / (25 + \sqrt{621}) \approx 1 / 25$) are 'planets' (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same size as that used in our Solar System." (Etangs & Lissauer, 2022).
2. "Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are 'brown dwarfs,' no matter how they formed nor where they are located." (Etangs et al., 2022).
3. "Free-floating objects in young star clusters with masses below the limiting mas for thermonuclear fusion of deuterium are not 'planets' but are 'sub-brown dwarfs' (or whatever name is most appropriate)." (Etangs et al., 2022).

This is a working definition and is destined to change as we discover and learn more about exoplanets. Our understanding of exoplanets has changed a lot since the idea of their existence was proposed back in the 16^{th} century. Years later, the first exoplanets were discovered in 1992; Poltergeist, Phobetor, and Draugr are three exoplanets orbiting a pulsar 1,957 lightyears from Earth. All three exoplanets were discovered through pulsar timing (NASA Exoplanet Catalog, n.d.). “Slight regular variations in the timing of the pulses indicate that the pulsar is moving back and forth, orbiting the center of mass of a system with one or more planets. Astronomers can deduce the orbit as well as the mass of these planets by precisely measuring irregularities in the timing of the pulsars.” (LCO, n.d.). This method is uncommon with exoplanet detection as there are more stars than pulsars. The main five detection methods include radial velocity, transit, direct imaging, gravitational microlensing, and astrometry; the transit method being the most used with 4,274 planets discovered (NASA 5 Ways to Find a Planet, n.d.). The transit method involves detecting the transit of a possible exoplanet in front of a star. The transit dims the star a measurable amount to where satellites and ground telescopes can observe the event. Data obtained from the observation is then plotted in a light curve to confirm the exoplanet’s existence. NASA TESS (the Transiting Exoplanet Survey Satellite), launched on April 18th, 2018, has helped to confirm 543 exoplanets with the transit method and has marked 7,204 as potential candidates (NASA Transiting Exoplanet Survey Satellite, n.d.). Unconfirmed candidates are put into the TOI (Tess object of interest) list to be reviewed by astronomers.

After reviewing a TOI, it is determined to be a false positive, in which the detection could have been caused by an NEB (nearby eclipsing binary), or a false alarm; or a true positive. True positive candidates are observed further, and reliable data can be collected to study what they are made of, how they formed, and what their conditions are like. Findings then help us shape the definition of an exoplanet and further the discovery for more, in the hopes of finding an Earth-like exoplanet that could support life.

Currently, there are no publications on TOI-5356.01, but a paper reviewing the candidate TOI-778 confirms the presence of a hot Jupiter with a similar radius to that of TOI-5356.01; 1.37 ± 0.04 $R_{Jupiter}$. The paper explains the discovery of the candidate during TESS's primary mission and lists the transit observations taken by the exoplanetary community. Radial velocity measurements were then taken to confirm the presence of the exoplanet (Clark et al., 2023). This discovery advances the discovery of exoplanets similar in size to that of TOI 5356.01.

In this paper, we present the follow-up observations of TOI-5356.01 which orbits its host star, TOI-5356. The parameters of this exoplanet are depicted below, in table 1. The goal of this observation is to determine whether the transit event occurs within the expected time, depth, and length.

Planet/Transit Parameters	Value
Orbital Period	~3.195 days
Depth	~4600 ppm
Duration	~3.79 hrs.
Radius	~13.32 R_Earth

Table 1: Transit and planet parameters of TOI-5356.01 (ExoFOP, n.d.)

In section 2, we present our observations gathered from TESS's archive and George Mason University's 0.8m telescope with a SBIG CCD camera. In section 3, we present our analysis of the TESS light curve of the exoplanet, and our ground-based light curve analysis. In section 4, we present the results of the light curve, while in section 5 we discuss the results. Finally, in section 6, we present our conclusions and potential future research.

2. Observations:

In Section 2.1, we present the TESS object of Interest 5356.01 and its exoplanet candidate properties, and host star properties gathered from the TESS input catalogue and ExoFOP archive. In Section 2.2, we present the TESS sector light curves gathered from the MAST exoplanet archive. In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1 Exoplanet properties

TOI-5356.01's discovery occurred during the fourth year of observations conducted by TESS. The satellite was observing sectors 43 and 44 from September 16^{th}, 2021, to November 6^{th}, 2021, and in that timeframe, the candidate was discovered (TESS year 4 observations, n.d.). TOI-5356.01 has a right ascension of 04:03:51.52, declination of +31:46:33.47, orbital period of 3.1948695 ± 0.03905 days, and a radius of 13.3231 ±0.773565 R_{Earth}. Its host star has a radius of 1.99656 ±0.0976882 R_{Sun}, a metallicity of -0.025 ±0.049 M/H, mass of 1.37 ±0.214024M_{Sun}, an effective temperature of 6577.37 ±111.24 K, and is 933.117 ±23.158 parsecs or 3043.420607 light years from Earth. TOI-5356.01 has a transit midpoint of 2569521.25817 ±0.0040831 BJD, a transit depth of 5.005909 ±0.003905mmag, and a duration of 3.786 ±0.312 hours (ExoFOP, n.d.).

2.2 TESS Sector Light Curves

Gathering .fits files from MAST, we were able to create a light curve through a python program inside of a Jupyter Notebook server. This curve's data was collected from TESS sectors 43, and 44. An enhanced curve is shown in Figure 1 at 3249.75 TBJD. The full light curve data set is shown in Figure 2, with the enhanced light curve being ~15.5 days on the X axis of the curve. This light curve had begun observation on October 17^{th}, 2023, and was released on December 4^{th}, 2023 (MAST, n.d.).

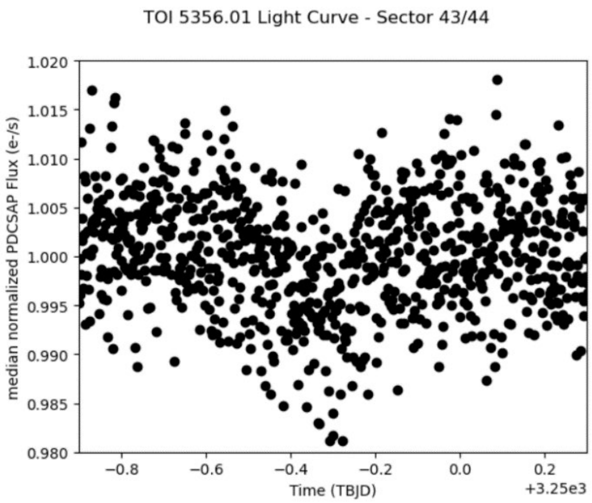

***Figure 1: Enhanced Light curve generated in Python** (MAST, n.d.)*

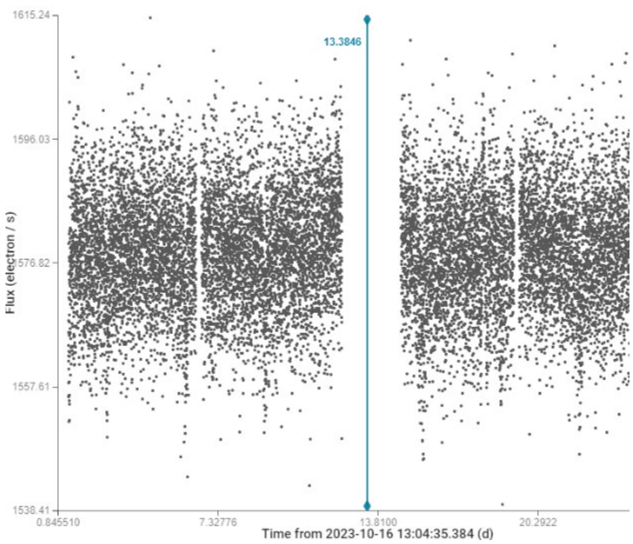

Figure 2: Full TESS observation light curve (MAST, n.d.)

2.3 GMU Ground-Based Observation Data

The candidate was observed on January 7th, 2023, at the George Mason University observatory. The observation started at 18:05 EST and concluded at 3:00 EST the next morning on January 8th. The Transit ingress had occurred at 18:34 and the egress occurred at 22:22. During the transit, 311 85 second exposures were taken using the telescope's CCD camera with the R filter. The total time of the observation lasted 6 hours and 55 minutes. The transit lasted 3 hours and 48 minutes.

3. Analysis:

In section 3.1, we present the tools used to analyze the TESS sector light curves using MAST data and python script. In section 3.2 we present the analysis of the ground-based light curve using the AstroImageJ software.

3.1 TESS Sector Light Curve Analysis

In Figure 1, above, a light curve that was found by a 2023 TESS observation is plotted via Python script. This specific curve is shown at the 15.6-day mark in Figure 2. Figure 2 is the full 26-day observation TESS made on October 16th, 2023. Several other curves are found within the plot, separated by ~3 days of data since the orbital period is ~3 days (NASA Exoplanet Archive, n.d.).

3.2 Ground Based Observation Analysis with AstroImageJ

Data Collection, Reduction, and Plate Solving

311 science exposures were taken by the GMU observatory, each 85.000 seconds long. Those sciences were data reduced from master dark and master flat images, created by the AIJ CCD Data Processer. We looked through each science photo to remove any bad images that had jumps, clouds, or some other event that ruined the data, and we were left with 262 sciences. Those sciences had to then be plate-solved so that the software knew where in the sky the photos were, and so any jump in the photo could be accounted for. Using a custom Astrometry.net server, AIJ was able to request data from the server to calculate which way the photos were oriented and where they were in the sky. Once plate-solved, the target star had to be located. Its RA and Dec coordinates were gathered from the NASA Exoplanet Archive and used in an image stack to find the target. The target star is pictured in Figure 3 below.

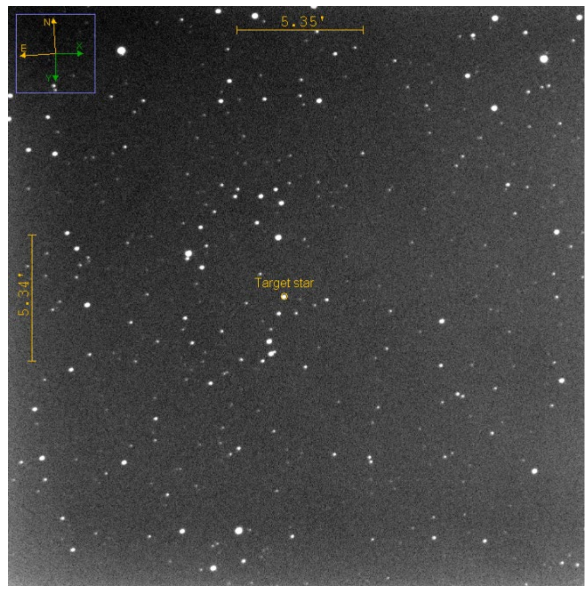

Figure 3: Target star pictured in middle at RA: 04:03:51.52 Dec +31:46:33.47

Light Curve Plotting and Fitting

After plate solving all 262 photos, an aperture was placed around the target star to generate a seeing profile. The seeing profile will be used to find comparison stars of similar sizes in the images. Using AIJ's multi-aperture measurements tool, fifteen reference stars were able to be placed, along with the GAIA stars that will later be used to check for NEBs. Figure 4 shows the seeing profile and Figure 5 shows the comparison stars (in red) and the GAIA stars (in green).

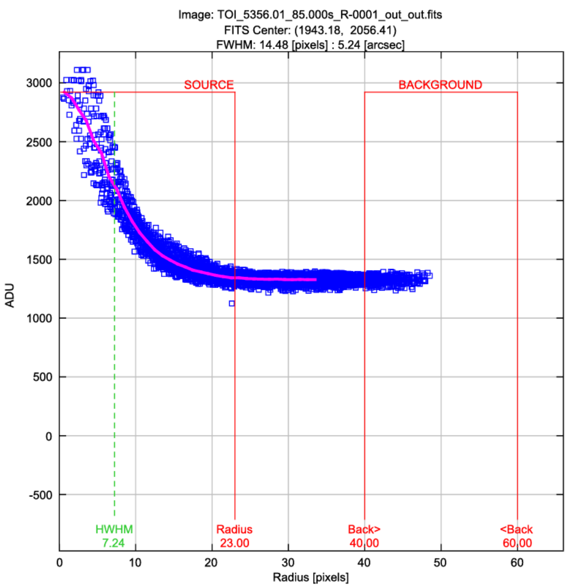

Figure 4: Seeing profile of target star. Aperture radius of twenty-three pixels

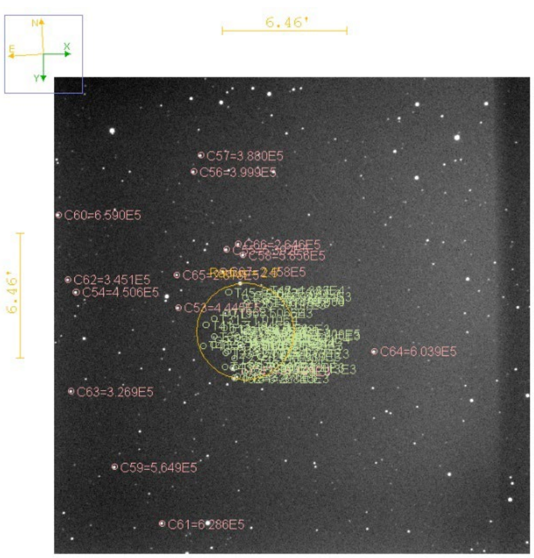

Figure 5: Reference stars (Red), GAIA stars (Green), GAIA field (Yellow)

Once the reference stars were placed, a light curve plot was generated using multi aperture photometry. Once AIJ went through all 262 photos, a plot config template was used to temporarily fit the data so it could be readable. A jump in photo 144 was found, causing the plate-solve for that image to fail. That image was removed from the data plot so it would not affect the results. We input stelar, planetary, and transit parameters into the multiplot main window, and data set two fit settings windows. The latter of which was to fit the target star data. The graph had plotted the predicted ingress and egress times (.4709 and 6288 BJD_{TDB} respectively). Using a the provided AstroImageJ tutorial for transiting exoplanet data-reduction and analysis, we were able to fit the rest of the plot to the data, correct the ingress and egress times to fit the curve, and plot reference stars (Plavchan et al., 2024). After fitting the plot, used the chi^2 and DoF (degrees of freedom) values to calculate the P-value to make sure the data fit the plot. The P-value was 0.04860 which meant the result was significant at $p<0.05$. We then compared the transit depth from the plot to the depth provided by the NASA exoplanet archive and got similar (plot: 4426.97, Archive: ~4600ppm) values, meaning the plot was accurate. Figure 6, in section 4, shows the final plot.

Before analyzing the plot for results, an NEB (Nearby Eclipsing Binary) check was required to see if the detection was caused by an NEB. The RMS and dmag plot is pictured in Figure 7 below in section 4. The NEB check result of the target star is pictured in Figure 8 below in section 4.

4. Results:

In this section, we present the results of the ground-based observation. The final plot is pictured in Figure 6, the NEB RMS and dmag plot is pictured in Figure 7 and the NEB check result for the target star is pictured in Figure 8.

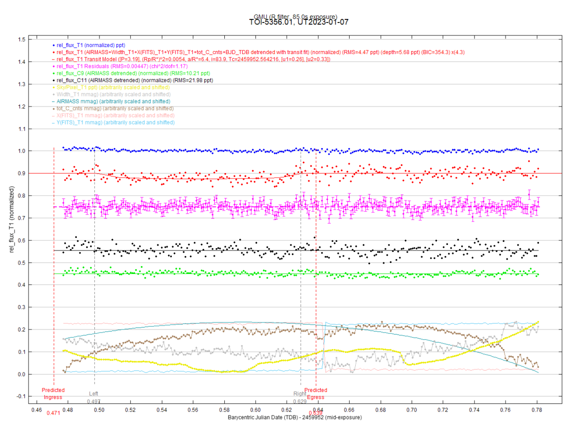

Figure 6: Final plot after fitting.

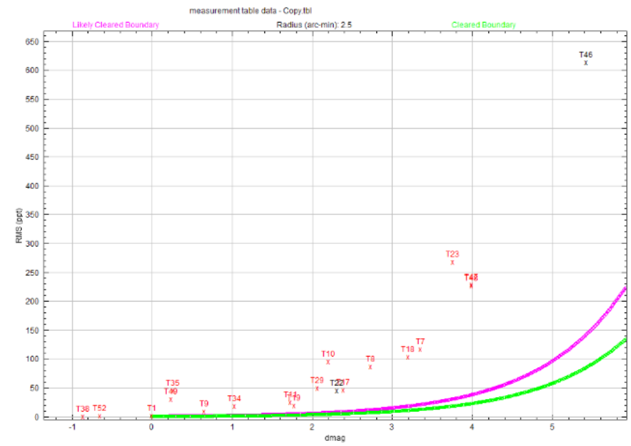

Figure 7: NEB check RMS and dmag plot.

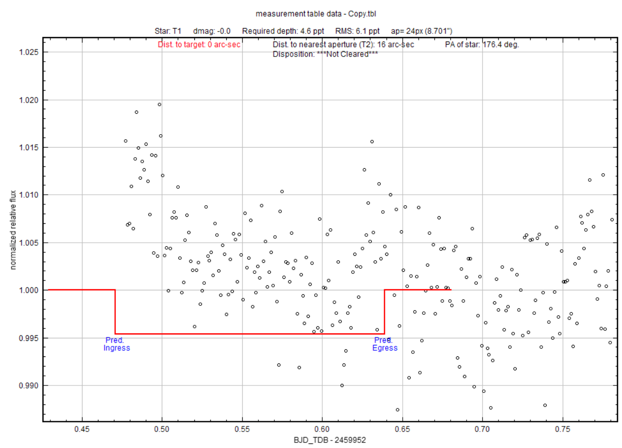

Figure 8: NEB check result for the target star

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

Based off the light curve from the TESS mission and the ground-based observation light curve, this candidate is likely to be a promising exoplanet. A ground-based observation cannot gather a significant enough curve to confirm the existence of an exoplanet. Comparing the reference stars to the curve of the target star, a slight curve can be seen within the predicted ingress and egress times, and a curve can be seen in the NEB check of the target star, leading to the conclusion that it is an exoplanet. However, due to the inconclusiveness of the RMS and dmag plot, we cannot confirm that this candidate is a true positive. The GAIA stars did not clear the NEB check, as their RMS values were too high. We are unable to rule out a false positive since we do not know if any stars were an NEB. Even if a curve is detected with some significance, we do not have enough evidence to say it was not an NEB.

5.2 Results in Context to other Candidates

Although this candidate cannot be confirmed with this data, other confirmed exoplanets share similar characteristics. TOI-5356.01 has a radius of 13.3231 ±0.773565 R_{Earth} and its host star has a radius of 1.99656 ±0.0976882 R_{Sun} which is similar to the confirmed exoplanet, WASP-73 b (ExoFOP, n.d.). This exoplanet is classified as a hot Jupiter and has a radius of 13.00234 R_{Earth}, and its host star has a radius of 2.07 +0.19/-0.08 (Exoplanet.eu, n.d.). Since these two exoplanets share comparable properties, it adds potential evidence to TOI-5356.01 being a real exoplanet.

6. Conclusions and Future Work

The Light curves generated by TESS and through the ground-based observation point to a promising exoplanet candidate with a curve of low significance. However, with an inconclusive NEB check, we are unable to confirm whether this candidate was a false positive or not. Similar confirmed exoplanets point towards the potential that this candidate is a true positive, but more work needs to be done in to confirm its existence.

Regarding the inconclusive NEB check, more observation on the surrounding stars needs to be done, with a larger telescope and longer exposure time. The curve in both plots were only significant enough to label 5356.01 as a promising exoplanet candidate. Future observations might need to be done with a clearer sky and with a more capable observatory, higher in altitude. Future work could include other methods as well that do not require more observations. A statistical analysis using codes like vespa could rule out a false positive. Different observational methods could be conducted to provide more diverse data. Such methods could be a direct observation in the infrared spectrum, or a radial velocity measurement which could provide more information about the star system. Any future analysis of the candidate would provide valuable information not only about the star and planet themselves, but also similar candidates.

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