Ground-Based Light Curve Follow-Up Observations of TESS Object of Interest 3521.01

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Abstract

The NASA Transiting Exoplanet Survey Satellite (TESS) has identified thousands of exoplanet candidates, including TOI-3521.01, a potential exoplanet orbiting a star approximately 762 parsecs away from Earth. This paper presents ground-based follow-up observations of TOI-3521.01 using the George Mason University 0.8m telescope. Through data reduction and multi-aperture photometry with AstroImageJ, we produced a light curve that indicates a possible transit event. Despite significant noise and challenges in data collection, the observed transit depth and duration align closely with predictions from TESS data. Although the light curve suggests the existence of TOI-3521.01, further analysis, including radial velocity measurements and absorption spectroscopy, is necessary to confirm the exoplanet and better understand its characteristics. We also discuss the limitations of our observations and recommend additional follow-up studies.

1 Introduction

The universe is home to countless planets, ranging from hot Jupiters to rocky worlds like our own. These planets located beyond our solar system are known as exoplanets (ESA, n.d.). Ever since the 1990s, scientists have been discovering exoplanets. Scientists have identified over 5,000 exoplanets to this day (NASA, n.d.). Discovering exoplanets enables deeper research on planets with habitable conditions, possibly providing details on evolution and how life develops (Kitchin, 11). Furthermore, understanding exoplanets is essential for understanding the stellar nature and evolution of the universe (The Planetary Society, n.d.). TESS, The Transiting Exoplanet Survey Satellite, is a NASA mission that is a part of the Explorers Program. In 2013, the TESS mission was approved and development began (GSFC NASA, n.d.). The TESS mission was aimed at identifying small planets with bright host stars while collecting data such as atmospheric quality (AstroB NASA, n.d.). Launch and regular science operations began in 2018. Over the next 2 years during the prime mission, TESS monitored over 200,000 main-sequence dwarf stars with its wide-field optical CCD cameras in order to detect transits (GSFC NASA, 2024). Originally a 2-year mission, the TESS mission was extended to 5 years and has since been observing the night sky (Reddy, 23). The TESS mission detects exoplanets using the transit method, which involves exoplanets passing in front of the host star and reducing the amount of light emitted. Graphically, this change can be observed on a light curve and can also include information on an exoplanet's atmosphere, as an exoplanet's atmosphere influences light dispersion (NASA, 2024). As of August 2024, only 542 of the 7,204 TESS candidates have been confirmed, highlighting the importance of follow-up observations of exoplanets (NASA Exoplanet Archive, 24). Ground-based follow-up validations are crucial in collecting more data that can be used to further research the possibility of life beyond Earth, how planets form, and their life cycles. Alternatively, validations can also be used to rule out false positives in exoplanet detection, increasing the accuracy of current analyses and data. No existing publications have verified or analyzed TOI-3521.01, making it a planetary candidate whose properties and existence are not known yet. In this paper, we present follow-up observations of TOI-3521.01. The exoplanet has an orbital period of 3.00 days and the planet radius is unknown. The goal is to determine the possibility of a transit during the expected time with the expected depth, as well as if TOI-3521.01 is a false positive or not. In Section 2 we present observations of TOI-3521.01 from the George Mason Univeristy 0.8m telescope and TESS. In Section 3 we present the AstroImageJ data processing involving data reduction and multi-aperture photometry. In Section 4 we will present our light curve results. In Section 5 we will analyze and discuss the light curve results. In Section 6, we will conclude and suggest possible future work.

2 Observations

In section 2.1, we present TESS data, including exoplanet and stellar properties, for TOI-3521.01. In Section 2.2, we present observational data collected from the George Mason University 0.8m telescope.

2.1 Candidate Properties

TOI-3521.01 was discovered by TESS in 2021 along with its stellar host TOI-3521. The stellar host TOI-3521 has a right ascension (RA) of 21h07m45.54s and a declination (DEC) of +31d46m51.42s. Its stellar effective temperature (T_{eff}) is 5757.3 K. The star is located 761.867 parsecs (2484.879 light-years) away from Earth. The exoplanet TOI-3521.01 has the following characteristics:

- Transit duration (T_{14}): 1.433 hours
- Transit depth: 10.7 ppt
- Equilibrium temperature (T_{eq}): 697 K
- Orbital period: 3.0002348 days
- Insolation flux ($S_{\oplus}$): 39.1931

Information such as stellar radius, stellar mass, and planet's radius were not published (NASA Exoplanet Archive, n.d.).

2.2 Telescope Data

Ground observations were collected on June 17, 2024, using the George Mason University 0.8m telescope equipped with the R filter. Exposure time was 90s the 209 exposures taken of the TOI. Observation began at 22:30 and ended at 4:30 for a total of 6 hours. Ingress began at 0:18 and ended at 1:44, for a total of 1 hour and 26 minutes.

3 Analysis

In Section 3.1, we present our use of AstroImageJ to reduce and plate-solve the raw images obtained from the George Mason University Observatory. In Section 3.2, we present the process of producing a light curve using the reduced and plate-solved data in AstroImageJ.

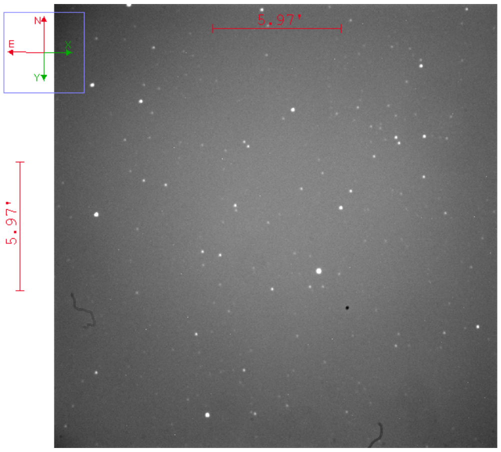

Figure 1: Raw Image

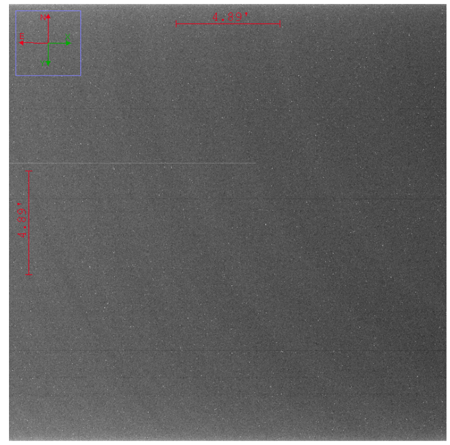

Figure 2: Dark Image

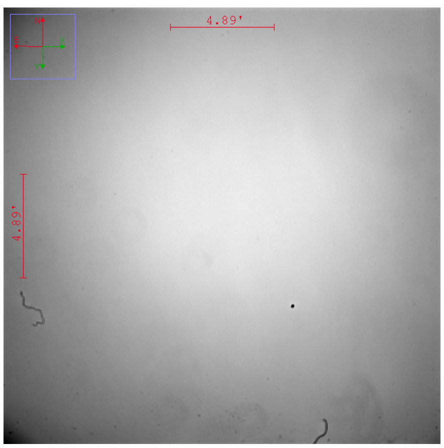

Figure 3: Flat Image

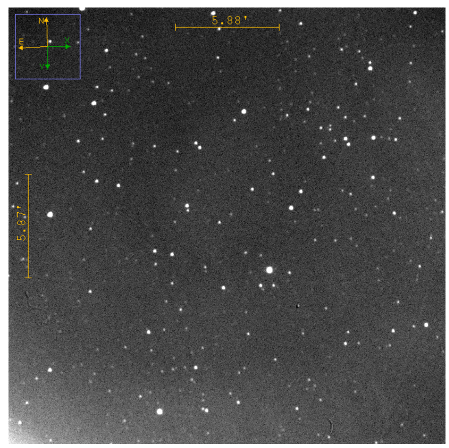

Figure 4: Reduced Image

3.1 Data Reduction and Plate Solving Utilizing AstroImageJ

We used the George Mason University 0.8m telescope to capture raw images of our TOI, such as the one shown in Figure 1, before utilizing the software AstroImageJ, a powerful image analysis software used to generate light curves and analysis of exoplanet transits (Collins et al.,2017). Before a light curve could be generated, AstroImageJ was used to lower the overall noise of the data set. Additional images, as seen in Figures 2 and 3, called darks and flats, are taken each night to accomplish this. Dark images, such as the one shown in Figure 2, are taken with the lens of the telescope closed, capturing both the inherent electric noise of the camera sensor and dust particles or smudges on the camera sensor. Additionally, flat images, such as the one shown in Figure 3, of a blank screen are captured to account for pixel-to-pixel sensitivity variations caused by dust or other particles. Several of these darks and flats are combined into one master dark and one master flat using AstroImageJ, further averaging the contents of both darks and flats. Next, in AstroimageJ the master dark image is subtracted from each science image before being divided by the master flat image. This results in an image such as Figure 4, or what we call a reduced image. Before extracting

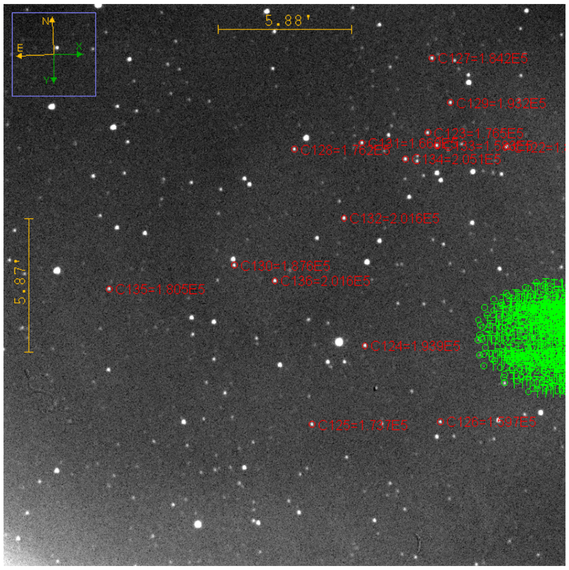

Figure 5: Final Plate Solved Image

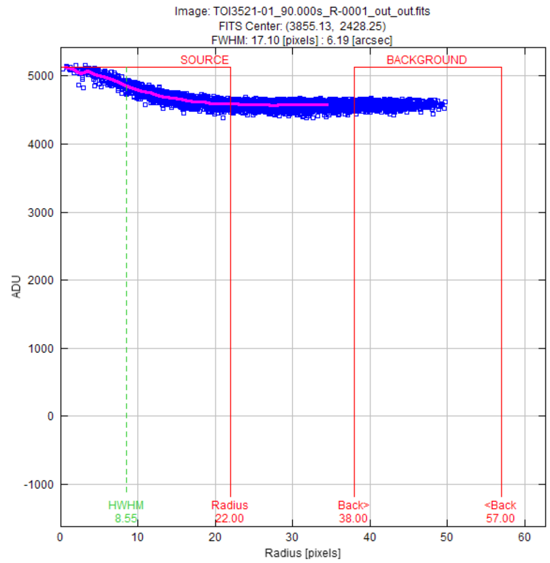

Figure 6: Seeing Profile

data from these images, we first need to locate the star that our TOI orbits around. To do this, we go through a process called plate solving. We first begin by downloading the local version of a star-matching catalog called Astrometry.net. Then, the NASA Exoplanet Archive (R. L. Akeson et al., 2013) is used to find our TOI's right ascension and declination values, enabling us to match them on our images and identify our target TOI, as shown in Figure 5.

3.2 Light Curve Generation

To create a light curve, we performed multi-aperture photometry to generate a table of data points. Multi-aperture photometry measures light within a specific aperture, typically a circular aperture of fixed size (Richmond. n.d). We determined the size of these apertures by generating a seeing profile for the TOI's star, shown in Figure 6. We utilized a base aperture radius of 22.00 pixels, a background annulus radius of 38.00 pixels, and an additional outer radius of 57.00 pixels. Furthermore, we placed a temporary 2.5' circle around our TOI, before uploading data from the ESA GAIA Mission, containing all possible nearby eclipsing binaries in the 2.5' circle. Finally, we used the "Multi-Aperture Measurement" tool to collect data from our TOI, GAIA stars in the 2.5' circle, and reference stars determined by AstroImageJ. Next, we prepared AstroImageJ to plot the light curve. We began by inputting data previously collected by TESS, regarding both the host star and the TOI, such as the TOI's orbital period and effective temperature of the host star; these values were 3.0002 days and 5757 K, respectively. Next, we entered the predicted ingress and egress times, starting in Universal Time Coordinated (UTC) with an ingress of 00:18 and an egress of 01:44. These times were then converted to Julian Dates (JD) and subsequently to Barycentric Julian Dates (BJD), using only the digits after the decimal point, which values were 0.682 and 0.741 respectively. After this, we configured our graph with the appropriate name and plotted and offset our detrending parameters to the bottom of the graph. These parameters included AIRMASS, representing how much sky we were looking through, and `tot_C_counts`, representing the number of images taken during a time. Following this, our raw science data under the name `rel_flux_T1` was added to the plot, alongside two comparison stars, C124 and C125. C124 and C125 served as references for how a flat light curve looks. Finally, a second version of `rel_flux_T1` was graphed, as well as the residuals for each point below, using a transit model with the detrending parameters AIRMASS, `Sky/Pixel_T1`, `tot_C_counts`, and `Width_T1`. These parameters were chosen after comparing different combinations and amounts of detrending to reduce the noise of the data without over-trending and substantially altering the data.

4 Results

In Section 4.1, we present the results of our ground-based light curve, and an example image containing streaks. In Section 4.2, we present the results of our NEB (Nearby Eclipsing Binary) check, containing the Dmag vs. RMS plot, and the overlay of the normalized relative flux depth over time for the target star.

4.1 Light Curve

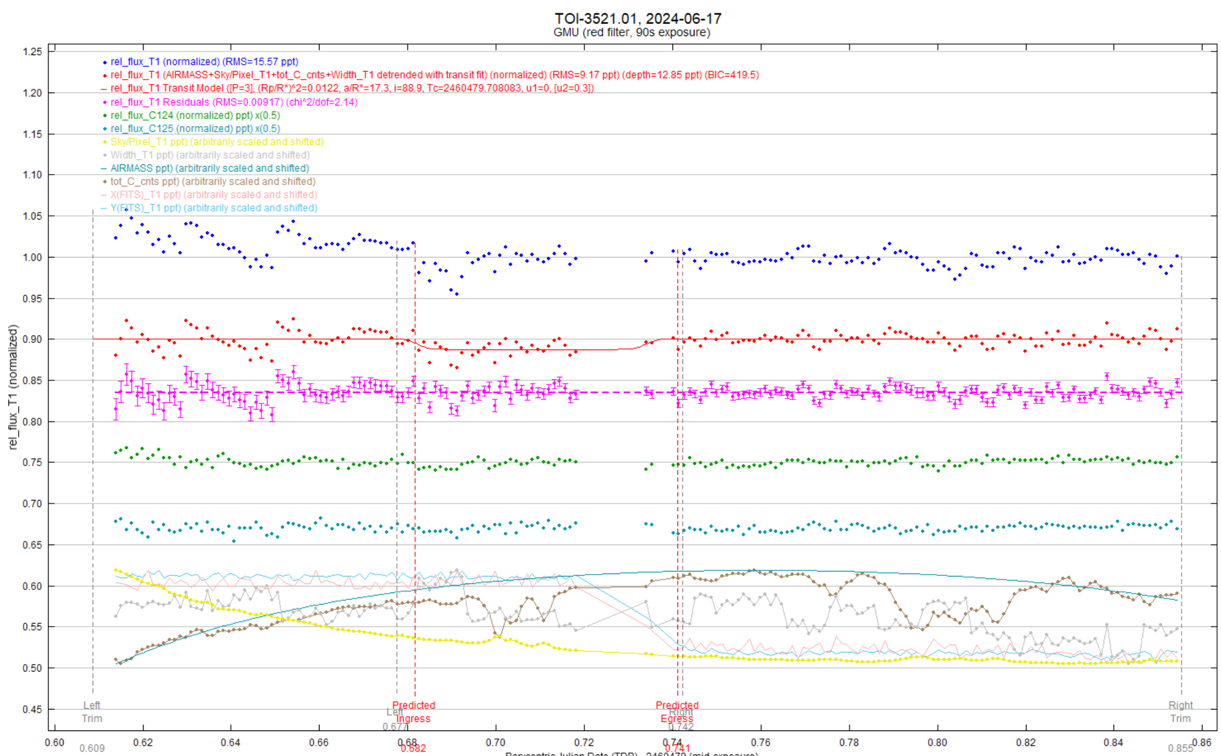

Figure 7: The light curve of TOI-3521.01 generated from data collected on June 17th, 2024. The noticeable dip in the flux indicates the possible transit of an exoplanet.

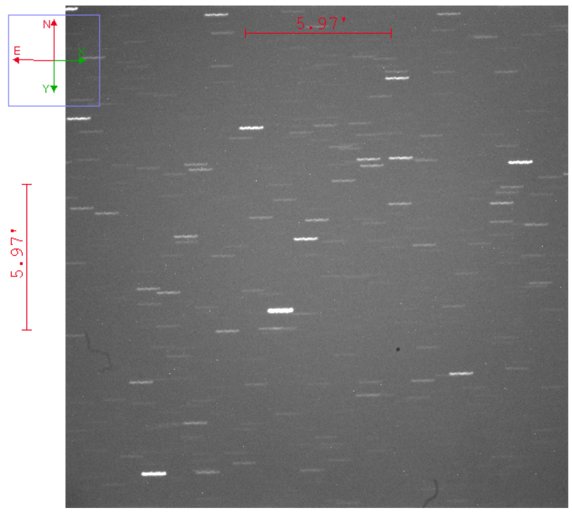

Figure 8: Example of an unusable image containing streaks

4.2 NEB Analysis

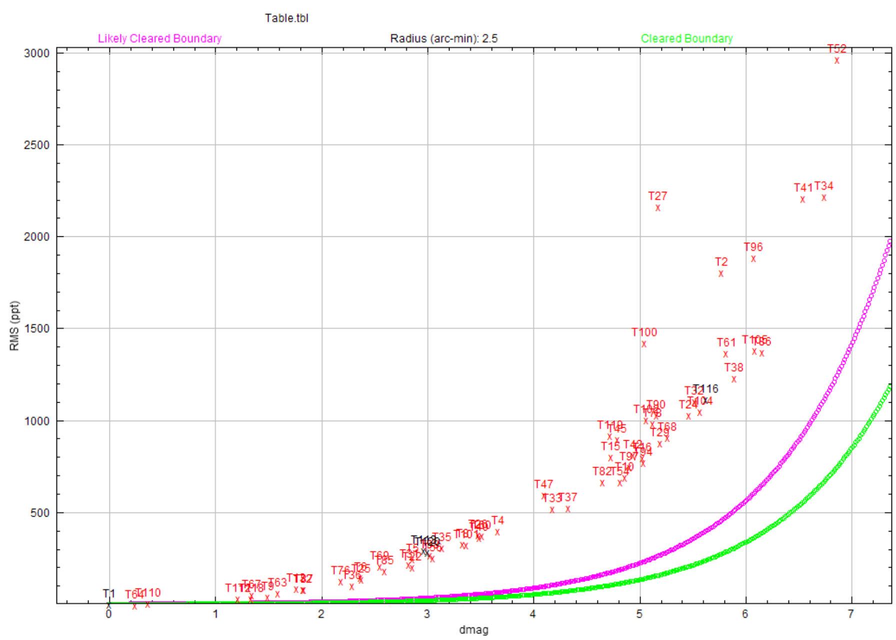

Figure 9: NEB (Nearby Eclipsing Binary) analysis for TOI-3521.01. This analysis checks for potential false positives in the exoplanet detection.

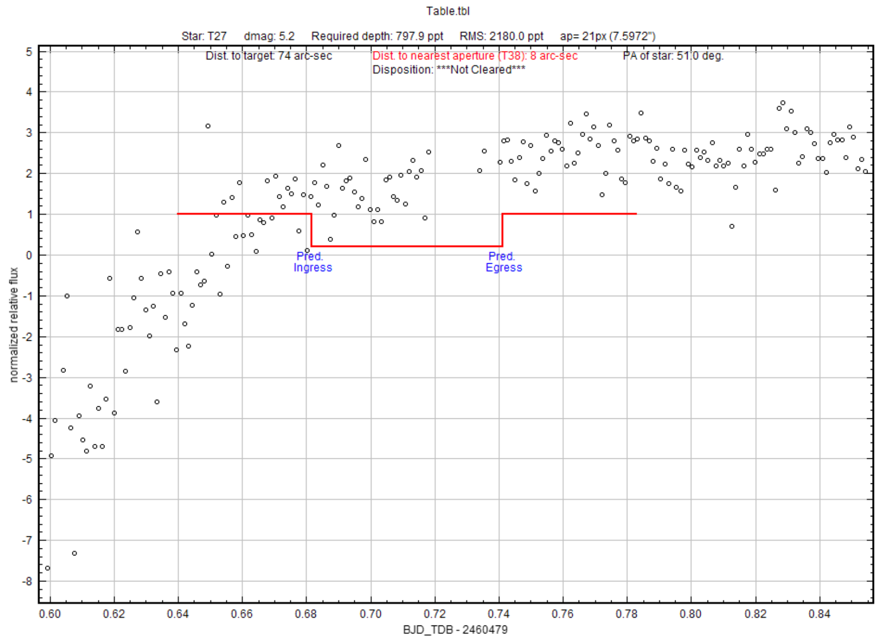

Figure 10: Overlay of the normalized relative flux depth over time for a possible NEB

5 Discussion

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

5.1 Interpretation of the Results

The light curve of TOI-3521.01 that was generated using data from June 17th, 2024, points towards the existence of TOI-3521.01. Due to the inherent noise of the data that we collected from the George Mason University Observatory, the RMS or Root Mean Squared value for the transit fit model applied to our data was relatively high at 9.17 ppt. However, large quantities of noise occurred before our transit contributed significantly to the high RMS value. This also likely skewed the χ^2/dof value, to a relatively high value of 2.14. Additionally, during the transit, beginning at approximately 0.720 BJD, a noticeable gap occurs in our light curve. This is caused by some of our science images being deemed unusable by us, like the example shown in Figure 8. These streaks have a wide variety of sources, most likely due to some kind of shift in weather, or a tracking error caused by shaking as the George Mason University Observatory tracks the star across the sky. Factors like these increased the amount of noise in the data and subsequently increased the RMS. However, even with the relatively high amounts of noise in the data, our light curve clearly shows a sign of a transit with a noticeable dip in the flux of our star. Additionally, our transit model predicted a transit depth of 12.85 ppt, which is still slightly off of the 10.7 ppt transit depth that the TESS team predicted for the night of June 17th. Furthermore, our model's ingress and egress times matched up with the predicted times extremely closely with a percent error of 0.425%, lasting 83 minutes, much like the predicted transit duration of 86 minutes. We attributed this error to the lack of images towards the second half of the transit. A NEB (Near Eclipsing Binary) check was conducted using AstroImageJ to detect if TOI-3521.01 was a false positive. This was done by analyzing the light curves of the GAIA stars in a 2.5' radius circle around TOI-3521.01 such as the light curve shown in Figure 10, of T27, a nearby star that stood out the most from the Dmag vs RMS graph. If there was a NEB in this circle, it is possible that it could cause a dip in our light curve and a false positive result. However, because the stars were too faint, which caused high scatter at the exposure time, it was not possible to tell if there was a false positive. This can be seen in Figure 10, where the light curve produced does not seem to be a NEB; however, the RMS of the graph is extremely high at 2180.0 ppt, rendering it unreliable. We cannot definitively say that TOI-3521.01 is not a false positive, thus the NEB check is inconclusive.

5.2 Comparison with Confirmed TESS Exoplanet Candidate

TOI-3521.01 has an orbital period of 3.0002 days, an effective temperature of approximately 700K, and a predicted radius that is 1.05 times the size of Jupiter. Based on this data, it cannot be classified as a typical gas giant variation, such as a Hot Jupiter. However, TOI-3521.01 shares some similarities with a confirmed exoplanet, HD 189733. HD 189733 is a Hot Jupiter with a radius 1.22 times that of Jupiter, an orbital period of 2.218 days, and an effective temperature of 1209±11K, and it transits a G-class star (Allen, n.d.). The similar sizes of these two planets suggest that if TOI-3521.01 is indeed an exoplanet, it might be classified as a Hot Jupiter. Nevertheless, further studies are necessary to determine essential properties such as its composition, mass, and density. These could be obtained through radial velocity and absorption spectroscopy measurements, which would provide valuable data regarding its composition.

6 Conclusions and Future Work

The light curve that we produced on data gathered from the George Mason University Observatory contains many features that point towards the likely existence of TOI-3521.01, such as a visible dip in the light curve, with a similar depth and duration, even despite a high RMS and χ^2/dof value due to large variance before the transit. Additionally, although the NEB check likely does not show signs of a false positive detection, it is not mathematically confirmable due to the lack of precision. We concluded that TOI-3521.01 likely exists; however, future work harnessing additional methods, specifically a more in-depth NEB check, as well as further analysis using methods such as radial velocity and absorption spectroscopy to uncover more information regarding the size, state, and makeup of TOI-3521.01, are strongly recommended.

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