Ground-based light curve follow-up validation observations of TESS Object of Interest (TOI) 3862.01

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Abstract

The Transiting Exoplanet Survey Satellite (TESS) searches for planets orbiting the brightest dwarf stars in space. These candidates require further analysis with ground-based work to be validated as actual planets. In this paper, we present a follow-up of the candidate exoplanet TOI-3862.01. The goal of this investigation was to see if the transit occurs on target as expected and ultimately confirm the planetary nature of TOI-3862.01. We observed the night sky with George Mason University's 32" telescope and conducted ground-based photometry using AstroImageJ to generate a light curve. While the nearby eclipsing binary (NEB) check was inconclusive, the noticeable dip in brightness and the results of the odd/even test suggest that the TESS detection is not a false positive. This indicates that TOI-3862.01 is likely an actual exoplanet and is worthy of further research for validation.

Introduction

An exoplanet is a planet outside of our solar system. They usually orbit other stars, although there are also free floating ones known as rogue planets [1]. Studying them can give us insight on how planetary systems form and develop, as well as possibly help us discover new forms of life. In 2018, 26 years after the first exoplanet was discovered, NASA launched the TESS mission. It does this by observing the night sky, looking for periodic changes in the brightness of stars. These events, called transits, occur when celestial objects like planets pass in front of a star and the observer. TESS detects these signals and creates a catalog of candidate exoplanets waiting to be validated as an actual planet through follow-up observations and analysis [2].

Since its launch, TESS has gathered data of over 7,000 potential exoplanets and their host stars. However, only 542 of those candidates have been confirmed so far as actual planets through ground-based follow-up observations [3]. Such recent discoveries include TOI-181b, a sub-Saturn exoplanet orbiting a K spectral type star, and TOI-1994b, a low-mass brown dwarf planet orbiting a subgiant star [4], [5]. The researchers of these investigations measured several of the planets' properties, including their radii, mass, period, eccentricity, and more. TOI-3862.01 is among the many that are still waiting to be validated as an exoplanet.

In this paper, we present follow-up observations of TOI-3862.01 (TIC 141205978.01). Our goals are to investigate whether or not the transit occurs on the expected star at the expected time with the expected duration and depth. We want to eliminate the possibility of TOI-3862.01 being a false positive and validate it as a planet.

In **Section 2**, we present our observations from TESS and the George Mason University 32" telescope. In **Section 3**, we present our analysis of the TESS light curve for TOI-3862.01 and our ground-based light curve analysis. In **Section 4**, we present the light curve results. In **Section 5**, we discuss our results. In **Section 6**, we present our conclusions and future work.

Observations

In **Section 2.1**, we present the properties associated with TESS Object of Interest 3862.01 and its host star as listed in the NASA Exoplanet Archive. In **Section 2.2**, we describe the ground-based observational data we collected.

2.1 - TOI Properties

TOI-3862 is located at a distance of approximately 249.02 parsecs [6]. It is estimated to have an effective temperature of 5343 K, making it a yellow, G-type star. It is similar in size to our Sun, with a radius of 0.93 Solar radii. The transiting planet in question, TOI-3862.01, has an orbital period of 1.557 days and a radius of 0.549 Jupiter radii, or 6.153 Earth radii. Its equilibrium temperature is 1212 K. The RA (right ascension) and DEC (declination) of the star are 12:23:36.14 and +50:32:40.65.

2.2 - Ground-Based Observations

The data for this research was collected on April 18th, 2022 (UTC) using the George Mason University 32" telescope with the R filter. The observation started at 00:49 and ended at 9:27. 222 exposures were taken of the target star, each one 65 seconds long. The science darks also had an exposure time of 65 seconds, while the flat darks and flats had an exposure time of 3.5 seconds.

Analysis

In **Section 3.1**, we present the tools we used to generate the ground-based light curve using AstroImageJ. In **Section 3.2**, we analyze the ground-based light curve using AstroImageJ.

3.1 - Tools Used to Generate Light Curve

AstroImageJ is an extended version of ImageJ, an image processing software, equipped with additional plugins useful for astronomical analysis [7]. It allows astronomers to process data, perform differential photometry on multiple stars at once, and plot measurements to create a light curve.

Astrometry.net is a calibration service that provides astrometric metadata for astronomical images [8]. Ansvr is a software that allows users to run a local version of Astrometry.net, which significantly speeds up the plate-solving process. Plate-solving is done to assign each object in an image with RA and DEC coordinates.

3.2 - Generating Ground-Based Light Curve

First, we visually inspected the science images for any streaking of the stars or cloud coverage that would be problematic in extracting the light curve. After removing the unusable images, we created the master darks and master flat necessary in reducing and plate-solving the sciences in AstroImageJ using the CCD Data Processor tool. The master dark and flat are necessary for cleaning up artificial, non-astrophysical distortions in the science images. They are used to reduce the appearance of dust on the sensors, noise, and vignetting. Before aperture photometry, we generated a seeing profile to see how big our aperture sizes would need to be (see **Figure 1** for seeing profile). We performed differential photometry on the target star and 6 other Gaia-identified stars around it in a 2.5 arcminute radius, as well as 8 comparison stars present in the processed images (see **Figure 2** for field of view). Comparison stars are those similar in size and brightness. Using the photometric measurements, we created the light curve by plotting the stars' brightness as a function of time (see **Figure 3** for light curve). Finally, we conducted an NEB check and referred to data available in the Mikulski Archive for Space Telescopes (MAST) to ensure the initial TESS detection was not a false positive (see **Figure 4** for dmag vs RMS plot, see **Figure 5** for MAST data).

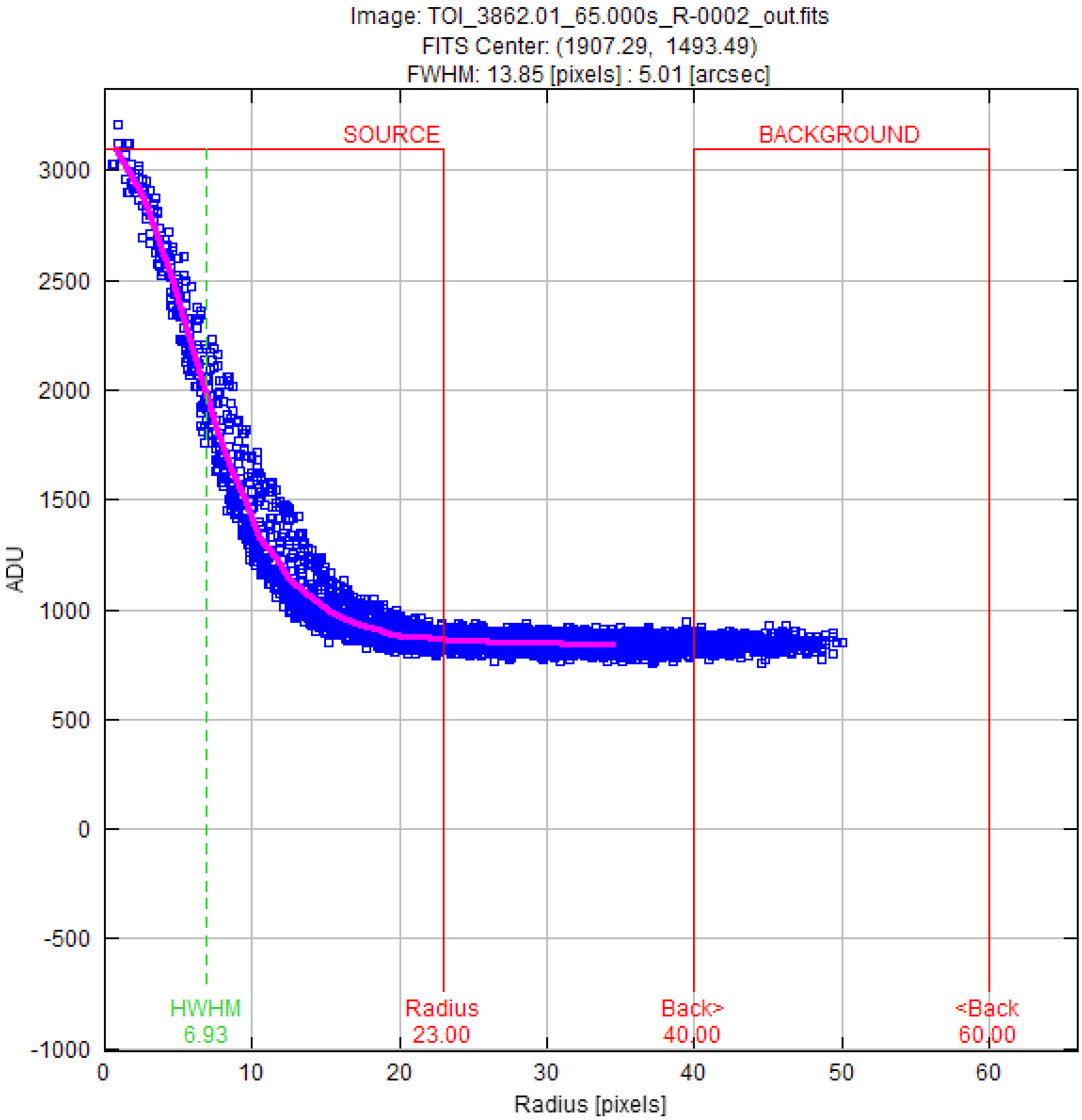

Figure 1: Seeing profile of TOI-3862.01 on AstroImageJ. Radius of the star in the image is 23 pixels, while the inner and outer annuli have radii of 40 and 60 pixels.

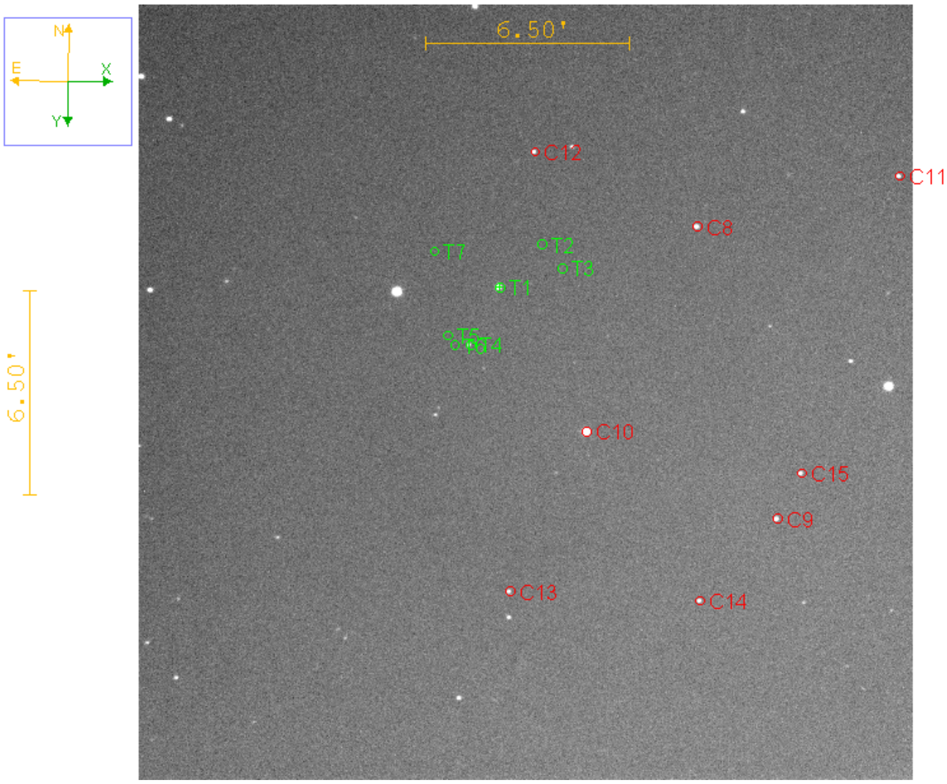

Figure 2: Field of view for TOI-3862.01. Target and neighboring stars identified by Gaia are marked in green. Comparison stars are marked in red.

Results

In **Section 4.1**, we present our results of the ground-based observation. In **Section 4.2**, we present the light curve from MAST.

4.1 - Ground-Based Results

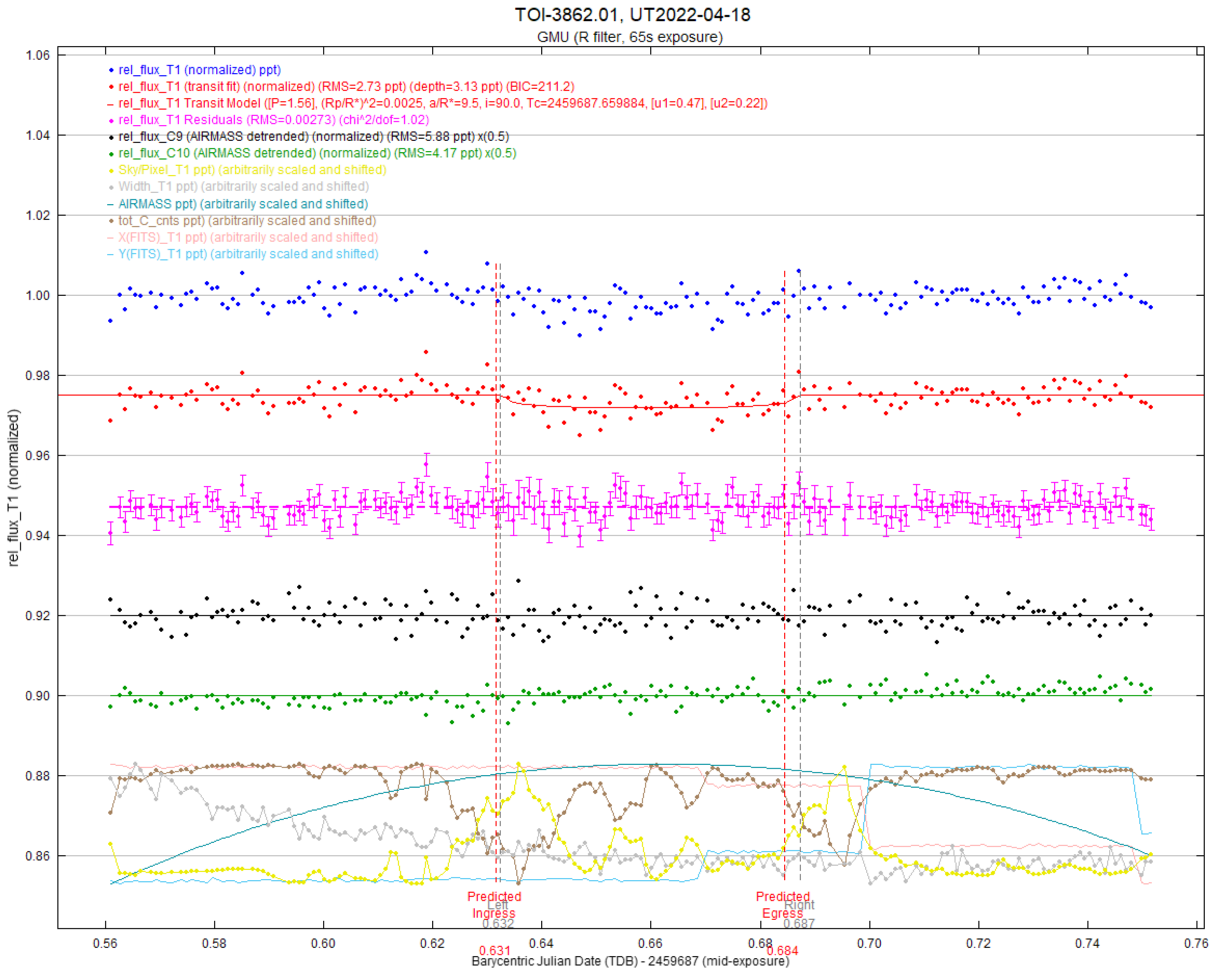

Figure 3: Light curve of TOI-3862.01. Comparison stars C9 and C10 are also shown. No parameters were detrended.

In the light curve, we included the raw measurements of the target star (shown in blue), the transit fit (red) with residuals (magenta), and two comparison stars with the least amount of scatter (black and green). At the bottom are the plots of several parameters that can be used to detrend the data as recommended in the TFOP (TESS Follow-up Observing Program) SG1 (Sub Group 1) Observation Guidelines [9].

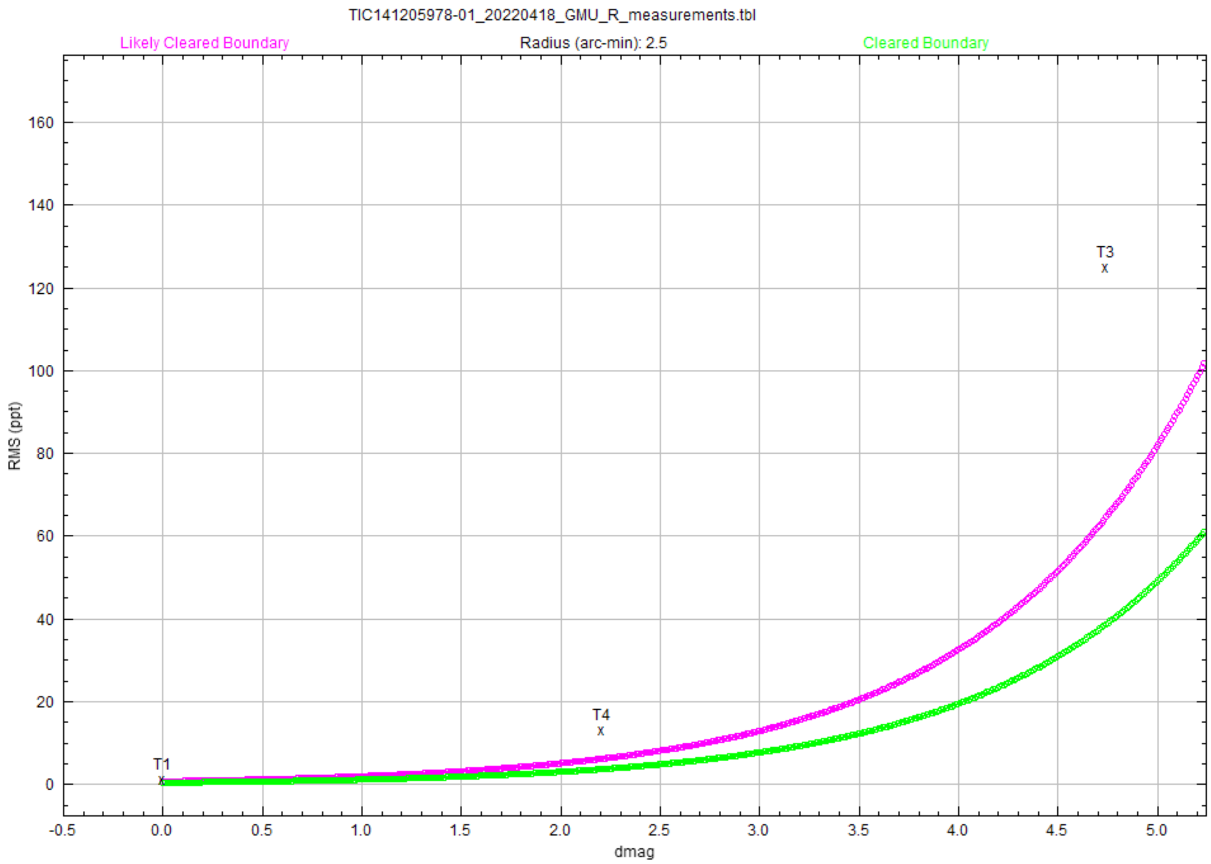

Figure 4: Dmag vs. RMS plot of TOI-3862.01 (T1) and neighboring stars (T2-T7).

None of the stars cleared the NEB check as they do not fall beneath the green curve. The dispositions of the stars are as follows:

T2: Not Cleared-flux too low

T3: Not Cleared

T4: Not Cleared

T5: Not Cleared-flux too low

T6: Not Cleared-flux too low

T7: Not Cleared-flux too low

Stars T2, T5, T6, and T7 are not visible in the science images, meaning their signal is too low to be reliable for accurate analysis. Thus, they have been excluded from the plot.

4.2 - MAST Light curve

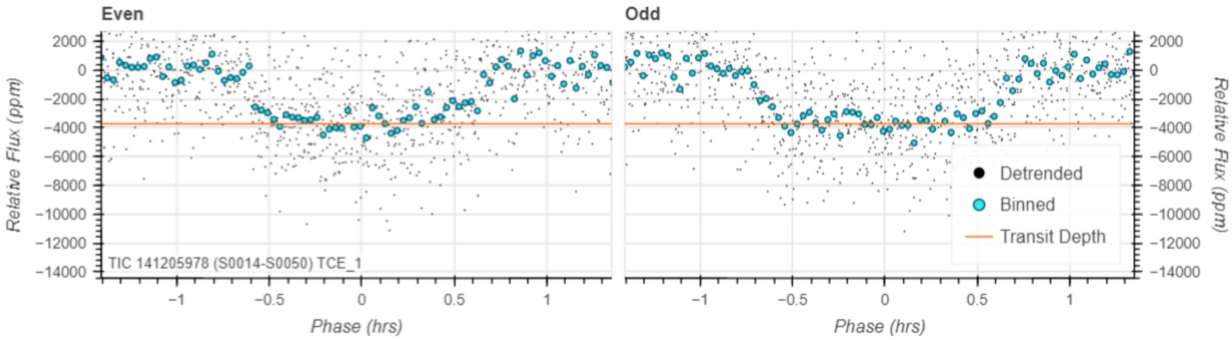

Figure 5: Folded light curve of TOI-3862.01 showing primary (odd) and secondary (even) transits. Plots are zoomed in on event. Obtained from MAST.

We referred to the light curves available on MAST after the NEB check to further check for the possibility of a false positive.

Discussion

In **Section 5.1**, we interpret our results. In **Section 5.2**, we place our results into context of the greater field of candidate exoplanet follow-up analysis for the TESS mission.

5.1 - Interpretation of Results

The ground-based light curve shows a clear flux of the target star with no breaks in the data. The depth of the transit came out slightly shallower (3.13 ppt) than predicted (3.9 ppt) by 0.77 ppt. The transit also occurred slightly later and lasted longer. The predicted ingress and egress times were 0.631 and 0.684 BJD_{TDB}, but the ground-based light curve shows that the transit occurred from 0.632 to 0.687 BJD_{TDB}. The transit model has a relatively low RMS (root mean square), an indicator of the amount of scatter in the data. An RMS value of 2.73 suggests that our data is not very noisy and hence more precise and reliable.

None of the surrounding stars identified by Gaia cleared the NEB check, so we cannot definitively say whether or not an eclipsing binary system is responsible for the TESS signal (see **Figure 4**). This is likely because we took photos with an exposure time appropriate for the target star, not the fainter neighboring stars. Since we cannot see the other stars very well, we are not able to properly measure their brightness. However, the stars do fall on a well-ordered curve similar in shape to the pink and green curves. This indicates that the NEB check could be successful with a bigger telescope and photos of longer exposure times that would actually capture the neighboring stars in the science images. Conducting an NEB check with better images would ideally result in all the stars ending up beneath the green curve. Alternatively, some stars may show themselves as outliers on the plot compared to the rest, and we would conduct further investigation to confirm if they are NEBs.

Another test that can be done to check for false positives is the odd-even test (see **Figure 5**). A primary transit is when an object passes in front of the star so the observer can see both the star and the object. A secondary transit is when the object passes behind the star so that the observer can only see the star. If the primary and secondary transits are of different depths, the changes in brightness may be caused by an eclipsing binary system, not an exoplanet. If the flux is due to an exoplanet, every transit should be of similar depth. This is because planets do not produce their own light, so the only change in brightness occurs when the planet is in transit. In eclipsing binary systems, we get different levels of brightness depending on where the stars are positioned because both stars give off light. When the orbiting star eclipses in front, we get a small dip in brightness. When the orbiting star passes behind, we get a bigger dip in brightness because we are only able to see one star.

In addition, the transits of exoplanets are typically U-shaped when plotted, while for eclipsing binaries they tend to be V-shaped. In both our ground-based light curve and the MAST light curve, the transits are not V-shaped but U-shaped. This further supports the hypothesis that TOI-3862.01 is an exoplanet.

5.2 - Results in Context

Based on its high temperature and extremely short orbital period, TOI-3862.01 could be a hot Jupiter orbiting very close to its host star. Size-wise, it is on the smaller side of other hot Jupiters that have been discovered. Most hot Jupiters tend to be similar in size to our solar system's Jupiter, if not bigger [10]. However, this does not completely rule out the possibility of TOI-3862.01 being a hot Jupiter. TOI-1431b is another exoplanet that has been classified as an "ultra-hot Jupiter." It, like TOI-3862.01, also has a short orbital period of 2.65 days and a high temperature of around 2370 K [11]. Such similarities suggest that TOI-3862.01 is also a hot Jupiter, albeit cooler than TOI-1431b. If it is not a hot Jupiter, it could be a Neptunian planet or a super Earth because it is relatively large (five to six times the size of our Earth).

Conclusions and Future Work

We have determined that TOI-3862.01 is likely an exoplanet. We provided more accurate times for the ingress and egress of the transit and further validated the initial data collected through the TESS mission. We have also found that TOI-3862.01 fits the profile of a hot Jupiter.

We believe TOI-3862.01 is an excellent candidate for further research. While we may have provided better clarity of TOI-3862.01 and its qualities, there are still many questions left to answer. In the future, we would like to conduct a successful NEB check by using bigger telescopes that have much more light-gathering power to collect better images with longer exposures. Further analysis is also needed to statistically rule out false positives by using codes such as VESPA (Validation of Exoplanet Signals using a Probabilistic Algorithm). Other TFOP Sub Groups can conduct more observations using techniques such as reconnaissance spectroscopy, radial velocity, and high-resolution imaging to provide more information about TOI-3862.01 and its host star.

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