Ground-based Follow-up Observations of TESS object of intrest TOI 3873.01

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Abstract

This study investigates TOI 3873.01, an extra-solar planet candidate discovered by the Transiting Exoplanet Survey Satellite, or TESS for short. Despite TESS having significantly contributed to exoplanet research, very little to no prior research has been done on this object. Data reduction techniques such as flat and dark calibration were used in AstroImageJ to produce scientific images; along with aperture photometry[1] and light curve analysis. The findings suggest that a hot Jupiter exoplanet orbits the star UCAC4 801-022341, supporting TOI 3873.01's exoplanet status. Also, the calculated ESM of this exoplanet exceeded the projected threshold for exoplanets deemed qualified for JWST spectroscopic follow-up. This study contributes to the growing body of exoplanet research and demonstrates the value of follow-up observations for TESS candidates. The confirmation and characterization of TOI 3873.01 will hopefully add to the diverse understanding of exoplanets and may help guide future discoveries for potentially habitable worlds outside the solar system.

Introduction

Mankind has been fascinated by stars for millennia. Searching for our place in the universe, we have propelled curious-minded people to make strides to better understand the history, and origins of the night sky [2]. Only in recent years, with modern technology and telescopes, have we been able to study and observe planets outside our solar system. This has raised the question: Does life exist outside of Earth?

The study of exoplanets is a new type of astronomical science that has allowed astronomers to gain insight about worlds outside of the solar system[3] helping us understand their differences and similarities. The most common method scientists use to detect exoplanets is by analyzing a star's "light curve." A light curve is created by measuring the brightness of a star over a period of time, and plotting it on a light curve diagram. An exoplanet transit occurs when a planet passes in front of its host star. This in turn leads to a drop in the brightness of a star as the planet passes across it, which ultimately creates a dip in the light curve. However, this doesn't always mean that an exoplanet transit has occurred. Additional information and analysis would need to be done to confirm that it isn't something else like an nearby eclipsing binary star (NEB) that would lead to a false positive[4]. Because of this phenomenon, when an exoplanet signal is initially detected, it is referred to as a "candidate" until follow-up observations can confirm its planetary nature. Due to the rise in exoplanet discoveries, many recent research papers have been published analyzing TESS exoplanet candidates[5, 6]. By measuring the depth, duration, and frequency of these dips, we can determine various properties of the exoplanet, such as its size, orbital period, and distance from its host star[7].

The Transiting Exoplanet Survey Satellite(TESS)[8] has been a huge leap for mankind and its knowledge of explanatory systems. Having launched in 2018, the TESS mission has identified over 7,000 exoplanet candidates[9]. Among those, close to 500 have been confirmed. Of these candidates is TOI 3873.01, which remains unconfirmed. As stated earlier, minimal research has been done. Only one published paper[10] has included it, but it did not explain anything specific or different, only that it was discovered.

In this paper, we present follow-up observations of TOI 3873.01. The primary goal is to investigate whether 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 3873.01 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 5.1, we aim to refine the system parameters and push for further JWST spectroscopic analysis, which requires an Emission Spectroscopy Metric (ESM) above 7.5[11]. This threshold is particularly important given the limitations in our current data. Through these observations and analyses, we hope to contribute to the ongoing effort to validate TESS candidates and expand our understanding of exoplanetary systems.

Observations

In Section 2.1, we discuss the observations and light curves generated by the TESS mission. In Section 2.2, we present the observations made by the George Mason University telescope. *Note.* The figures were imported from the MAST (Mikulski Archive for Space Telescopes) portal. The data described here may be obtained from the MAST archive at TOI 3873.01.

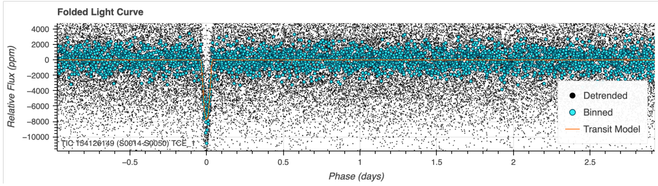

Figure 1: *TESS Median Detrended Time Series*

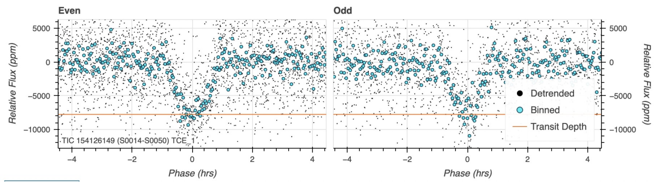

Figure 2: *TESS Even-Odd Light Curves*

TESS Observations - 2.1

TESS also generated light curves of TOI 3873.01. **(Figure 1)** shows the relative flux in ppm over time in days. The flux of ≈ 8100, matches our expected flux by NASA ExoFAST. **(Figure 2)** shows the even odd transits of the candidate exoplanet. Even odd light curves are important as they can prove other transiting events like NEBs or Nearby Eclipsing Binaries wrong. If the even light curve plot showed a higher flux than the odd light curve plot, it would be evident that a different transit had occurred that was not an exoplanet transit. However, due to the fact that both the even and odd fluxes match, it proves that TOI 3873.01 has a high likelihood of being a true positive.

GMU Observations - 2.2

Ground based observations of TOI 3873.01 were done using the 32in Ritchey-Chretien telescope at George Mason University with a KAF-16803 CCD camera collecting photons through the Red filter.

Collecting the data was a fairly simple process. Using ASCOM drivers[12] and The SkyX software, we were able to remotely control the entire observatory. A python script was then used to remotely operate the entire exoplanet imaging session. The final reduced images for each were then plate solved using astronomy.net and ready to go for scientific analysis.

Analysis

In Section 3.1, we present the steps and methods used for generating our light curve on TOI 3873.01 using AstroImageJ.

Analysis steps - 3.1

i. First, we downloaded the data from the GMU telescope taken on June 21st, 2024. A total of 156 sub frame lights were gathered, each of which were 90 seconds long in duration.

ii. Then, we performed data reduction on the data. These frames were individually calibrated with 20 dark frames and 20 flat frames in AstroImageJ[13]. The goals of image reduction are to remove detector effects from the data; including image noise, optical defects like dust, or amp glow from the camera sensor. In this way the end results are always clean, lower noise images.

iii. Next, we plate solved the science images. Using Astronomy.net as our star database, we centered each image based off its RA and DEC coordinates in the sky.

iv. We then loaded scientific subframes into AstroImageJ as a virtual stack

v. After locating the transiting star on our image, we created a seeing profile to confirm the aperture size on the star.

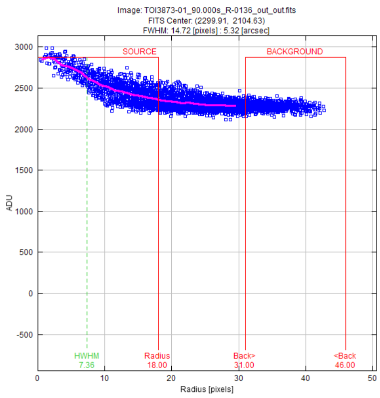

Figure 3: *Seeing profile during the observation.*

vi. We proceeded to use the multi-aperture tool in AstroImageJ which creates other apertures based of star brightness[1]

vii. Next, we imported light curve template into main plot. This gave a starting ground for further analysis and tweaking of the plot.

viii. Importing prior known exoplanet data (ExoFop) was done next to help increase accuracy of data plot

ix. Lastly, we applied many adjustments including using Linear LD u1 and Quad LD u2 values (Eastman et al, 2013) to plot windows to get the correct fit for the transit curve

x. For the NEB plot, we imported nearby Gaia stars from the Gaia database to use as apertures to perform a check for any Nearby Eclipsing Binaries.

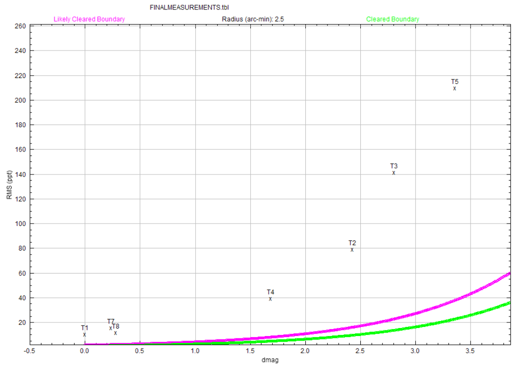

Figure 4: *NEB check plot*

Taking a look at the NEB plot, due to the fact that no stars lie under the boundary line, we cannot rule out the fact of a Nearby Eclipsing Binary.

Results and Data

In Section 4.1, we present the final light curve from the GMU telescope data, as well as its analysis. In Section 4.2, we present the parameters of the planet exoplanet from a variety of sources.

Looking at the light curve **(Figure 5),** many different plots are visible. The first plots the normalized flux between the transiting star and the reference stars in the image. The third flux depicts the fitted transit model.

- $(R_p/R_*)^2 = 0.0133$ is the square of the planet-to-star radius ratio.
- $a/R_* = 22.3$ is the semi-major axis to stellar radius ratio.
- T_c is the time of transit center.
- u_1 and u_2 are limb darkening coefficients.

The fourth plot shows the differences between the observed data and the transit model. The RMS of residuals and chi-square per degree of freedom (χ^2/dof) indicates how well the model fits the data. The rest are not as important so I will go through them quickly. The fifth plot shows the SPOC PDC

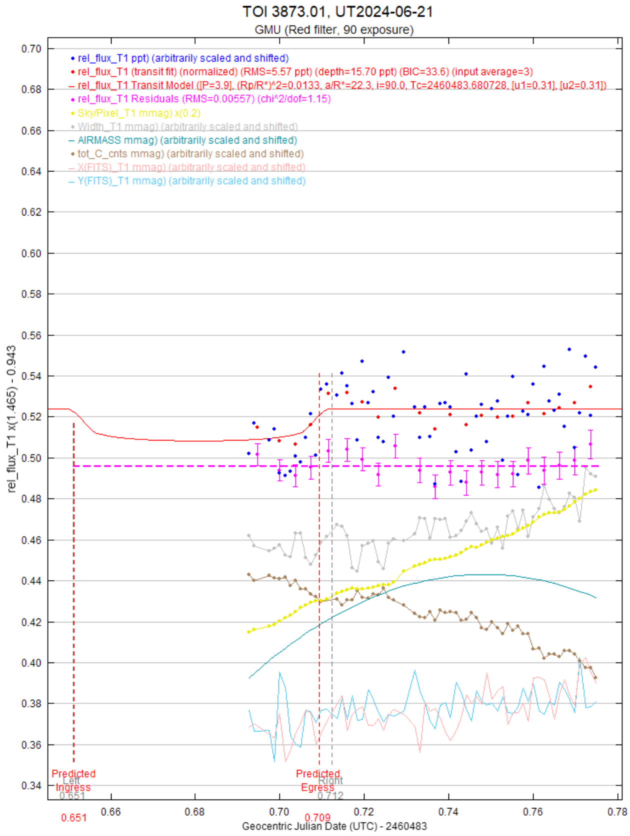

Figure 5: *GMU (Red filter, 90s exposure) light curve of TOI 3873.01 transit on UT2024-06-21 - 4.1*

(Presearch Data Conditioning) flux, which is a processed version of the light curve used to remove systematic errors. The sixth plot displays the transit width. The seventh plot illustrates the airmass, indicating the amount of atmosphere the light passed through during the observation. The eighth plot represents the total counts, which can be used to check for overall brightness trends or instrumental effects. The ninth plot shows the X-axis pixel position of the target star in the image over time. And the tenth plot displays the Y-axis pixel position of the target star over time.

Discussion

In the Results and Data section, we presented our interpretation of the results. In this section, we place our results into context of the greater field of follow-up of candidate exoplanets from the NASA TESS mission. In Section 5.2, we push for further JWST spectroscopic analysis by calculated TOI 3873.01's ESM.

From the light curve **(Figure 5),** it is clear a dip in brightness has occurred. It is also evident that the predicted ingress and egress were accurate, with only a minor correction for the egress. Also, the predicted

Table 1: *TOI 3873.01 Parameters - 4.2*

Parameter	Value	Source
Predicted Ingress	10483.6513	TESS Follow Up Working Group
Predicted Egress	10483.7093	TESS Follow Up Working Group
Orbital Period (days)	3.90	TESS Follow Up Working Group
Predicted Duration	1.386 $\pm$0.303	ExoFOP IPAC Caltech
$R_\oplus$	14.7	NASA ExoFAST 2023
Temp(K)	6071	NASA ExoFAST 2023
T_{eq} (K)	1114	ExoFOP IPAC
Depth(ppt)	9.78$\pm$0.047	ExoFOP IPAC Caltech
V mag	13.13	TESS Follow Up Working Group
K mag	11.655 $\pm$0.024	ExoFOP IPAC

transit length of 1.386±0.303 hours roughly matches our data. The ingress at 0.651 and egress at 0.710 we measured in UTC which translates to around 1.416 hours. For an exoplanet to be classified as a hot Jupiter, We also know that this exoplanet is 14.7$R_\oplus$. This means that it is over 14 earth masses, indicating it is indeed a good possibility that it could be a hot Jupiter. The observed star to planet ratio squared of 0.0133 corresponds to $\approx 1 - 2\%$ decrease in the star's flux during the planet's transit. This significant drop in flux is consistent with the transit of a large planet, supporting the classification of TOI 3873.01 as a potential hot Jupiter.

Emission Spectroscopy Metric - 5.2

The Emission Spectroscopy Metric (ESM) is a great tool for analyzing an exoplanet's potential for further spectroscopic observations, in particular, spectroscopic observations with the James Webb Space Telescope, or JWST. Developed by Kempton et al. (2018), the ESM provides a quantitative measure of the expected signal-to-noise ratio for a planet's thermal emission spectrum. The formula is given by:

$$\text{ESM} = 4.29 \times 10^6 \cdot \frac{B_{7.5}(T_{\text{day}})}{B_{7.5}(T)} \cdot \left(\frac{R_p}{R}\right)^2 \cdot \left(\frac{1}{10^{m_K/5}}\right) \quad (1)$$

where $B_{7.5}(T)$ is Planck's function evaluated at a wavelength of 7.5 μm and temperature T, T_{day} is the planet's dayside temperature (typically estimated as

1.10 times the equilibrium temperature), T is the host star's effective temperature, R_p/R is the planet-to-star radius ratio, and m_K is the host star's apparent magnitude.

The scaling factor of 4.29×10^6 is calibrated to the JWST MIRI LRS instrument. A higher ESM value indicates a better candidate for spectroscopic follow-up, with values above 7.5 considered particularly promising for JWST observations.

In the context of the ESM calculation, we use Planck's function to determine the amount of radiation emitted by both the star and the planet at a specific wavelength (7.5 um in this case) given their respective temperatures. This helps us estimate the contrast between the planet and star, which is crucial for determining how detectable the planet's spectrum will be.

For TOI 3873.01, we can use this metric to evaluate its suitability for future spectroscopic studies, potentially providing insights into its atmospheric composition and thermal properties.

We can plug in values from **Table 1**, with the star temp at 6071K, planet-to-star radius ratio of .0133, T_{eq} K of 1114, and the K-band magnitude of 11.655, into the ESM equation to get:

$$\text{ESM} = 4.29 \times 10^6 \cdot \frac{B_{7.5}(1225.4\text{K})}{B_{7.5}(6071\text{K})} \cdot 0.0133 \cdot \left(\frac{1}{10^{11.655/5}} \right) \quad (2)$$

Using Planck's law to calculate $B_{7.5}(T)$ for both temperatures:

$$\begin{aligned} L_{7.5}(T_{\text{day}} = 1.1 \cdot T_{\text{eq}}) &= L_{7.5}(1.1 \cdot 1114\text{K}) \\ &= L_{7.5}(1225.4\text{K}) \\ &\approx 55.49382 \text{ W/m}^2\text{-sr-um} \end{aligned}$$

$$\begin{aligned} L_{7.5}(T_*) &= L_{7.5}(6071\text{K}) \\ &\approx 565.85654 \text{ W/m}^2\text{-sr-um} \end{aligned}$$

Plugging these values into our equation:

$$\begin{aligned} \text{ESM} &\approx 4.29 \times 10^6 \cdot \frac{55.49382}{565.85654} \cdot 0.0133 \cdot \frac{1}{10^{11.655/5}} \\ &\approx 4.29 \times 10^6 \cdot 0.09801 \cdot 0.0133 \cdot 0.0099 \\ &\approx 24.2 \end{aligned}$$

With an ESM of ≈ 24.2, TOI 3873.01 exceeds the recommended number of 7.5, making it qualified for further JWST spectroscopic analysis.

Conclusions and Further Work

From our results and discussion, it is evident that TOI 3873.01 is a confirmed exoplanet. Furthermore, based on our observations and analysis, we conclude that TOI 3873.01 is a strong candidate for classification as a hot Jupiter exoplanet.

The evidence supporting this conclusion is substantial: the planet's radius of 14.7 Earth radii places it firmly in the gas giant category, while its short orbital period of 3.90 days and high equilibrium temperature of 1114 K indicate a close orbit around its host star. The significant transit depth of 15.70 ppt is also consistent with a large, Jupiter-sized planet.

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