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Article

Ground-based Follow-up Observations of TESS Exoplanet Candidates

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SUMMARY

The goal of this study was to further confirm, characterize, and classify LHS 3844 b, an exoplanet detected by the Transiting Exoplanet Survey Satellite (TESS). Additionally, we strove to determine the likeliness of LHS 3844 b and similar planets as qualified candidates for observation with the James Webb Space Telescope (JWST). We accomplished these objectives by analyzing the stellar light curve, theoretical emission spectroscopy metric (ESM), and theoretical Planck spectrum of LHS 3844 b. We remotely obtained pre-reduced ground-based data of LHS 3844 b from the El Sauce Observatory. We hypothesized that LHS 3844 b and similar target TESS candidates are qualified for future JWST follow-up. Through AstroImageJ and the Python programming language, we converted the calibrated data images into normalized and fitted flux light curves. Through our best-fit light curve model, we classified LHS 3844 b as a terrestrial planet. The calculated ESM of LHS 3844 b surpassed the projected threshold for simulated planets deemed qualified for JWST spectroscopic follow-up, and the Planck spectrum of LHS 3844 b revealed that the observed wavelengths between 6,000 and 10,000 nanometers would produce the highest signal-to-noise spectroscopic observations of LHS 3844 b and like planets. These findings will improve the accuracy and efficiency of spectroscopic follow-ups performed by the JWST, and we intend to apply these methods to study a variety of exoplanets.

INTRODUCTION

The search for similar solar systems and life beyond Earth's solar system has fascinated human beings for centuries (1). The study of exoplanets, planets that orbit a star other than the Sun, provides us with crucial information regarding planetary population characteristics and the differences between Earth's solar system and other solar systems (2). Exoplanets orbit their host stars for measurable periods, and can therefore be detected through predicted planetary transits. Planetary transits occur when a planet crosses the disk of its host star and causes a decrease in the observed amount of light emitted from the host star. A transiting exoplanet can be detected by observing the light flux emitted from a star over a given period of time, typically hours (3).

The recent development of new technologies and equipment has allowed for further exploration and discovery of exoplanets using the transit method. A clear example of this advancement is the Transiting Exoplanet Survey Satellite (TESS), an Explorer mission launched by the National Aeronautics and Space Administration (NASA) in April of 2018 with the goal of detecting exoplanets specifically using the transit method (4). TESS utilizes the Science Processing Operations Center (SPOC) pipeline to convert raw data images into calibrated pixels and transit light curve graphs (5). In the span of two years, TESS will monitor at least 200,000 stars for intervals lasting from a month to a year for signs of planetary transits (4). The goal of TESS is to detect planets that orbit M dwarf stars, as these stars are geometrically more likely to host Earth-like and potentially habitable planets because of their relatively small sizes and low effective temperatures (6). Additional follow-up analyses are performed on TESS exoplanet candidates to confirm the existence of the planets, rule out false positives, and establish precise transit parameters. Scientists around the world complete follow-up analyses through observatories such as the Las Cumbres Observatory Global Telescope Network (7).

A target TESS candidate is an Earth-like planet orbiting an M dwarf star. TESS is targeting these planets because there is a greater chance they orbit within the habitable zone of their host star (4). LHS 3844 b orbits LHS 3844, an M dwarf star with 0.151 $M_\odot$ and 0.189 $R_\odot$, and is therefore considered a target TESS candidate. A relatively large fraction of planets detected by TESS will likely hold similar properties as LHS 3844 b. A projected thermal emission spectroscopic signal-to-noise or ESM value of 7.5 is required for model simulated planets to qualify for James Webb Space Telescope (JWST) follow-up (8). JWST spectroscopic analysis concerns the emission spectrum of a planetary system, and consequently, the JWST will observe secondary transits, which is the passage of a planet behind the disk of its host star. During a secondary transit, there is a slight decrease in the detected amount of emitted light from the system due to the disappearance of the planet's emitted light, which allows for the precise analysis of the planet's individual emission (9).

A Planck spectrum represents the spectral density of electromagnetic radiation emitted from an object in thermal equilibrium. The theoretical Planck spectra of a planet and its host star can be used to determine the wavelength range in which to observe the highest signal-to-noise of the

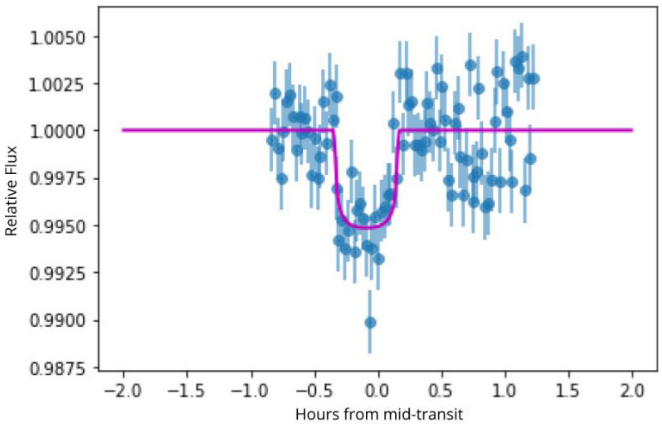

Figure 1. Normalized and modeled transit light curve graph of LHS 3844 b. Error bars represent the 1σ error bar ranges of the host star's flux values, as generated by AstroImageJ.

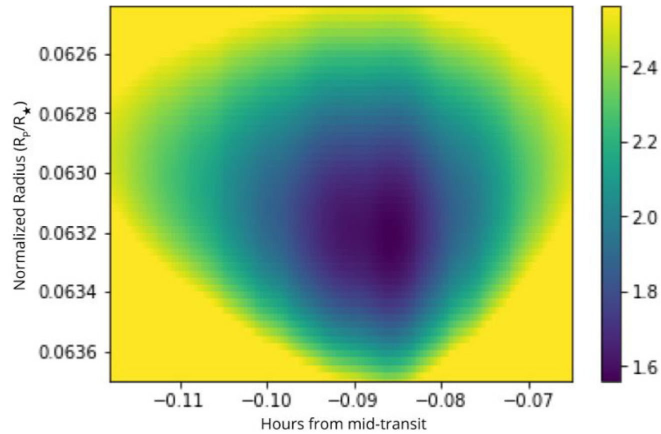

Figure 2. Chi-squared map used to determine the 1σ error bar range (68% Confidence Intervals) for all planetary parameter calculations.

planet's emission. It is crucial to identify the exoplanets that would produce the highest signal-to-noise spectroscopic observations in order to improve the methodology of these spectroscopic follow-ups and account for the substantial amount of exoplanet candidates to be observed during the JWST timeline.

The objective of this study was to analyze pre-reduced ground-based follow-up data on LHS 3844 b to further confirm, characterize, and classify the planet. We will also study the preferred spectroscopic observation conditions of target TESS candidates. We hypothesized that LHS 3844 b is qualified for future spectroscopic observations with the JWST.

RESULTS

Light Curve Analysis & Classification of LHS 3844 b

To analyze the radius and time of mid-transit of LHS 3844 b, we created the normalized and fitted transit light curve graph for the planet (**Figure 1**). We found a reduced chi-squared value of 1.5 for the data set of LHS 3844 b. The chi-squared map for these data of LHS 3844 b (**Figure 2**) was used to determine the 1σ error bars (68% confidence intervals) for all of the planetary calculations.

We calculated the transit depth (RP/R*) of LHS 3844 b to be 0.0632 ± 0.0008, which is consistent with the previously published literature value of 0.0640 ± 0.0007. However, the detected mid-transit time for LHS 3844 b (-0.087 ± 0.031 hours from the expected time) differed from the literature with statistical significance (10).

Along with the radius, the mass of an exoplanet is essential in characterizing and classifying the planet. The mass of a planet is typically determined by analyzing the amount of gravitational force the orbiting exoplanet exerts on its host star through the radial velocity method (11). Since radial velocity measurements have not been taken for LHS 3844 b, we used an empirical relationship between the radius in Earth radii (RΘ) and mass in Earth mass (M_Θ) of archived exoplanets to roughly project the mass of LHS 3844 b as 4.0 ± 1.8 M_Θ (**Figure 3**) (12, 13).

With our calculated radius and projected mass values, we used standards from the Planet Habitability Laboratory to classify LHS 3844 b as a terrestrial planet orbiting an M dwarf star (14). The planetary parameters of LHS 3844 b are summarized to compare them to the literature values (**Table 1**).

Expected Spectroscopic Quality of LHS 3844 b

To determine the validity of LHS 3844 b for spectroscopic observation with the JWST, we calculated the planet's ESM. A higher ESM value represents a larger S/N, and therefore, a more qualified planetary candidate for JWST follow-up. The ESM value for LHS 3844 b was calculated to be 43, which greatly surpasses the projected ESM threshold of 7.5 for model simulated planets that were deemed qualified for JWST follow-up (15).

Planck Spectrum of LHS 3844 b

To determine the wavelength region that would provide the most accurate spectroscopic observations of LHS 3844 b, we plotted the theoretical Planck spectra of LHS 3844 b and its host star (16). The theoretical Planck spectra of LHS 3844 b and its host star approach each other and exhibit similar slopes between the wavelengths of 6,000 and 10,000 nm (**Figure 4**).

DISCUSSION

The planetary parameters of LHS 3844 b classify it as a rocky planet orbiting an M dwarf star. The detected mid-transit time for LHS 3844 b (-0.087 ± 0.031 hours from the expected time) differed from the literature with statistical significance, indicating that the period of this planet can be constrained further with future analysis. This variance in mid-transit time may be the result of the gravitational pulls of an additional planetary body orbiting LHS 3844 or a large uncertainty on

Parameter	Value	Source
Orbital Period (days)	0.4629279 ± 0.0000016	Vanderspek et al., 2018
Inclination (degrees)	88.22 ± 0.30	Vanderspek et al., 2018
Equilibrium Temperature (K)	805 ± 20	Vanderspek et al., 2018
RP/R*	0.0632 ± 0.0008	This work
Semi-major Axis (AU)	0.0062 ± 0.0002	Vanderspek et al., 2018
Radius (R_{Θ})	1.30 ± 0.06	This work
Projected Mass (M_{Θ})	4.0 ± 1.8	Roques, 1995

Table 1: Parameters of LHS 3844 b.

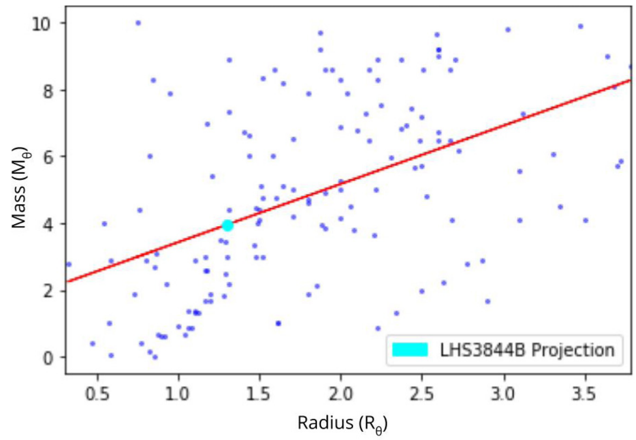

Figure 3. Empirical relationship between the mass in Earth mass (M_{Θ}) and radius in Earth radii (R_{Θ}) of archived exoplanets. This relationship was used to project the mass of LHS 3844 b. The r2 value for this data set is 0.25, signifying that the best-fit linear model is 25% matched to the data.

the cited period (10). Additionally, since only one transit was observed, this variance in mid-transit time may be caused by stochastic M dwarf star pulsations, although this cannot be concluded until more transits are observed (17). The normalized radius of LHS 3844 b (0.0632 ± 0.0008) was calculated to be consistent with the literature value.

Its theoretical ESM value and Planck spectrum support our hypothesis that LHS 3844 b and similar target TESS planets will likely be considered qualified candidates for future JWST spectroscopic follow-up. Furthermore, the ESM and Planck spectrum suggest that the JWST should observe target TESS systems in the mid-infrared wavelengths between 6,000 and 10,000 nm to obtain the most accurate information regarding the emissions and atmospheres of these exoplanets. The general wavelength region between 6,000 and 10,000 nm provides the greatest S/N of the planet's emission and therefore indicates the observed wavelengths that would produce the most detectable thermal emission spectra of LHS 3844 b. In this wavelength region, the light emitted from the host star does not overpower the emission from the planet, making it easier to accurately isolate and study the thermal emission of LHS 3844 b. These factors propose that the most accurate spectroscopic observations of LHS 3844 b will be obtained by observing the planetary system's emissions between the wavelengths of 6,000 and 10,000 nm. The JWST will conduct spectroscopic observations in the wavelengths between 600 and 25,000 nm; constraining the wavelength region in which to analyze this target TESS exoplanet class will greatly improve the efficiency and reduce the cost of the JWST data analysis process.

This information will aid in the process of proposing methodology to study atmospheric biosignatures and the molecular compositions of Terran planets in general. LHS 3844 b was the first planet orbiting a Red Dwarf star detected by TESS that was released to the public; more analysis of other detections must be completed before drawing conclusions about the general population of TESS objects and their viabilities for further analysis with the JWST. This classification indicates that LHS 3844 b is a target TESS candidate. Consequently, a relatively large fraction of TESS-detected exoplanets will likely be similar in size and period to LHS 3844 b and will produce similar spectroscopic results. The methods used in this study can be applied to other exoplanetary systems to gain a better understanding of the measures that can be taken to improve the JWST data analysis methodology for a larger variety of TESS exoplanet candidates. In addition, radial velocity observations of LHS 3844 may be taken to constrain the measurements of LHS 3844 b's mass and orbital period. The limitations of this study lie in the lack of repeated observations regarding the transit of LHS 3844 b. This lack of available data may result in large uncertainties in our measured values.

With the recent launch date delays and prolonged testing state, the JWST is now at an anticipated total cost of $8.835B, which exceeds the $8B maximum that Congress set for the mission in 2011 (18). The JWST has allocated $837M towards five years of operations and two additional years of data analysis (19). Knowledge of the precise wavelength regions to study will increase the efficiency of the data analysis process, and may aid in reducing the cost of the JWST.

METHODS

TESS utilizes the SPOC pipeline to convert raw data images into calibrated pixels and transit light curve graphs. The stages of the SPOC pipeline consist of data acquisition, calibration, photometry, presearch data conditioning, transiting planet search, and data validation (5). In this study, we developed a data processing pipeline modeled off of the SPOC pipeline with the stages of data acquisition and calibration, photometric analysis, light curve modeling, and light curve analysis.

Data Acquisition & Calibration

We analyzed pre-reduced ground-based data of the

TESS exoplanet candidate, LHS 3844 b; these data were remotely obtained through the Las Cumbres Observatory Global Telescope Network. This full transit of LHS 3844 b was observed through the IC band on UT 2018 September 06 by the El Sauce Observatory Planewave Corrected Dall-Kirkham (CDK) 0.36-meter telescope located in El Sauce, Chile (20).

Photometric Analysis

We used the photometry software AstroImageJ to stack the data images of LHS 3844 b's star field and perform aperture photometry, light measurement within a fixed size, on the target star (LHS 3844) and neighboring comparison stars (21). The flux measurements of the target star were normalized in regards to the flux of the comparison stars to rid the data of atmospheric disturbance errors. These normalized flux measurements of the target star were then converted into numerical values of relative flux:

$$relfluxT = \frac{F_T}{\sum_{i=1}^{n} F_{Ci}}$$

where FT is the differential light flux count of the target star, n is the number of comparison stars, i is the measurement of the current comparison star, and FCi is the net integrated counts of the current comparison star.
The measures of relative flux for each image were stored in text files along with the corresponding barycentric Julian date and 1σ error bar value:

$$\sigma_{relfluxT} = \frac{F_T}{F_E}\sqrt{\frac{N_T^2}{F_T^2} + \frac{N_E^2}{F_E^2}}$$

where FT is the net integrated counts of the target star, FE is the sum of net integrated counts of all comparison stars, NT is the noise in the target star aperture, and NE is the ensemble noise in all comparison star apertures.

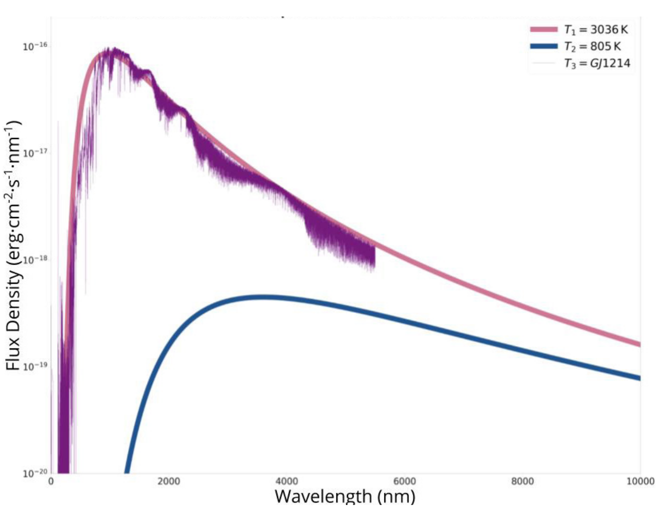

Figure 4. The theoretical Planck spectra of LHS 3844 and LHS 3844 b are plotted over the spectrum of GJ 1214, a star that has the same spectral type (M4.5) as LHS 3844.

Light Curve Modeling

Utilizing the Python programming language, we used the numerical flux and 1σ error bar values generated by AstroImageJ to create the transit light curve graph of LHS 3844 b. To study the light curve in terms of relative flux and transit depth, we normalized the baseline of the transit light curve to a value of one. We proceeded to use a Python package titled BATMAN to fit multiple light curve models to our data set of LHS 3844 b; these models were varying based on a given range of values for the radius and time of mid-transit parameters within the Python code (22). All other parameters used to create the best-fit light curve were based off of the previously published literature results from the initial TESS detection of LHS 3844 b (10).

Chi-squared goodness of fit tests were then performed on each data to model pairing:

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - \mu_i)^2}{E_i^2}$$

where k is the number of sets of data points, i is the current set of data points, Oi is the observed transit data point, μi is the point on the predicted light curve that correlates with Oi, and Ei is the associated error (23). The purpose of this statistical test was to find the chi-squared value closest to one, which would signify a strong data to model fitting.

Since the transit light curve graph of LHS 3844 b is in terms of relative flux, we used the detected decrease in stellar flux to calculate the planet's normalized radius (RP/R*):

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2$$

where ΔF is the observed change in flux and F is the stellar flux (24).

Emission Spectroscopy Metric

Kempton et al. (2018) recently developed an analytic emission spectroscopy metric (ESM) to quantify the expected signal-to-noise ratio (S/N) of a given planet's thermal emission spectroscopic measure:

$$ESM = 4.29\times10^6 \times \frac{B_{7.5}(T_{day})}{B_{7.5}(T_*)} \times \left(\frac{R_p}{R_*}\right)^2 \times 10^{-\frac{m_K}{5}}$$

where 4.29×10^6 is a scaling factor for the JWST infrared bandpass, B7.5 is Planck's function evaluated for a given temperature at a representative wavelength of 7500 nanometers (nm), Tday is the planet's dayside temperature in Kelvin ($1.10\times T_{eq}$), T* is the host star's effective temperature in Kelvin, RP/R* is the normalized planetary radius, and mK is the apparent magnitude of the host star in the K band. A predicted ESM threshold was determined from model simulated TESS exoplanets such that the population would yield approximately 300 high-quality candidates for follow-up with the JWST (25).

We used the ESM and predicted threshold to determine whether or not LHS 3844 b is likely qualified for future JWST spectroscopic observation.

Planck Spectra

Planck's Law is given at a certain wavelength (λ) and Kelvin temperature (t), and it assumes that the given object behaves as a blackbody, which is an entity that hypothetically emits radiation in all wavelengths:

$$L(\lambda, t) = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda t}}-1\right)}$$

where h is Planck's constant (6.63×10^{-34} Js) and c is the speed of light (2.99×10^{8} ms^{-1}) (16).

We plotted the spectrum of GJ 1214 to act as a guideline for the theoretical Planck spectrum of LHS 3844; these two stars are the same spectral type (M4.5), and will therefore produce similar spectra (26). In addition, we overplotted the theoretical Planck spectrum of LHS 3844 b to assess the observed wavelength range that would produce the highest quality emission spectroscopic measure of LHS 3844 b and like planets.

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