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253990973

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ABSTRACT

The study and characterization of exoplanets provides indispensable insight into the nature of our universe. Each new planet confirmed represents an extension of human knowledge and understanding of how planets form behave. The purpose of this paper is to characterise the exoplanet orbiting star TIC 253990973. All the characterization of this stellar system was done using data taken from ExoFOP TESS and Simbad, making use of various telescopes. The modelling of the system was done using EXOFAST v2. The model fits the data provided very well, characterising a solar-type star with a tidally locked planet in a highly circular, extremely close orbit. Due to the planet's proximity to the star, it is extremely hot at a T_{eq} of 2640 K. The star also has a smaller companion of one seventeenth its brightness, and this additional star diluted the transit data. The planet is therefore slightly larger than the data would lead us to believe.

Keywords: planetary systems, 253990973

1. INTRODUCTION

As long as humans have observed the skies we have wondered about planets around other stars. The first exoplanet was discovered in 1992 (Wolszczan & Frail 1992), and since then the search has gained many adherents, and the rate of exoplanet discovery has grown exponentially. This is due to the fact that studying exoplanets provides a wealth of new information about how planets form and how life could develop. New technologies and devoted missions (like TESS) have made this process easier and more accessible than ever before. The purpose of this paper was to determine if TESS Planet Candidate TIC 253990973 is a real exoplanet, utilizing the public data available on the ExoFOP page and then modeling it in EXOFAST. In this paper, the process of modeling and analyzing TESS data will be discussed in depth. This will be followed by a summary of the interesting characteristics of this stellar system.

2. OBSERVATIONS

I used all the relevant observations available from the ExoFOP TESS page on my planetary system. This includes the stellar temperature (Teff), mass, radius, luminosity, and parallax. The planetary characteristics I used were epoch, period, and radius.

2.1. *TESS*

I used data from TESS Sector 13 to model the star. The data was taken on 2021-10-29. TESS, or the Transiting Exoplanet Survey Satellite, is a satellite in orbit around Earth and the Moon. It surveys the sky in sectors, and stares at each for a month, searching for transiting exoplanets. Once a candidate is identified, it is recorded and can then be confirmed by people modeling the TESS data.

2.2. *SED Photometery*

I looked at EXOFOP TESS for photometry, and all the data referenced in sections 3.2.1 and 3.2.2 was taken from there. The astronomical equipment used to collect the data consists of TESS, GAIA, and all four WISE telescopes.

3. METHODS

3.1. *Software Downloads*

First I had to update EXOFAST v2, and then I had to install lightkurve. Note that I would've had to install python3 at this stage, but since I have a mac it was already downloaded.

Then I made a directory called 'modeling', with another directory inside it whose name is the TIC ID of my star. After this, I downloaded TESS LC.

3.2. *Preparing Files*

All the files mentioned below were copied from the HAT-3 example.

3.2.1. *Modifying .sed File*

I copied it and then renamed the copy using my stars TIC ID. Then I edited it by replacing the data already in the file

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with the corresponding data from my star. This data was retrieved from the 'Magnitudes' section of the ExoFOP page. I also ensured that the formatting of the new data was the same as in the original file.

3.2.2. *Modifying .prior File*

I copied this file and renamed it using my stars TIC ID, following the same procedure as for the SED file. I edited this file by changing the following fields to match ExoFOP page: epoch (tc), period, stellar mass (mstar), stellar radius (rstar), and effective temperature (Teff). I also added the parallax from Simbad.

3.2.3. *Modifying .args File*

I copied this file the same way as done above. I edited it to change to which files it pointed. Priorfile became '$HOME/modeling/253990973/253990973.priors', prefix became '$HOME/modeling/253990973/fitresults/253990973.', and tranpath became '$HOME/modeling/253990973/*SPOC.dat'. I deleted fittran, fitrv, circular, nomist, and torres. Then I also added ntemp = 8 and changed maxsteps to 5000.

I was meant to add in the path to the mistsedfile (setting it equal to '$HOME/modeling/253990973/253990973.sed'), but I forgot and did it later on in the process.

3.3. *Iteration*

Then I ran the fit, and the first few times it did not work due to some errors with the original prior file. However, those were resolved and when I ran the fit successfully, it yielded a good stat.sed.eps and mist model, but I could not identify a transit in my transit file. So, I changed the python code to remove the flatten and remove outliers lines, and I zoomed in on the path so that the dip in the data would be more evident. I also realized that there was no path to the mist.sed file in py prior file, so I added it. After that, I ran the fit again with much more success. At that point, I changed the star's mass (mstar) in the prior file to make the model fit the data expressed in the MIST file, and after those iterations, I changed the prior file to the new one created by the fit. The one I ended up using was called 253990973.priors.3, because I ran one full fit before finishing the iteration process. The fit I ran using the new prior file was very successful.

4. RESULTS

My fit confirmed that there is an exoplanet orbiting the star.

4.1. *Transit Graph*

The transiting exoplanet is very visible in figure 1, although the transit depth is very small. This is due to the extremely small size of the planet relative to it's star. In addition to that, the transit is also being diminished because of the star's companion providing additional light.

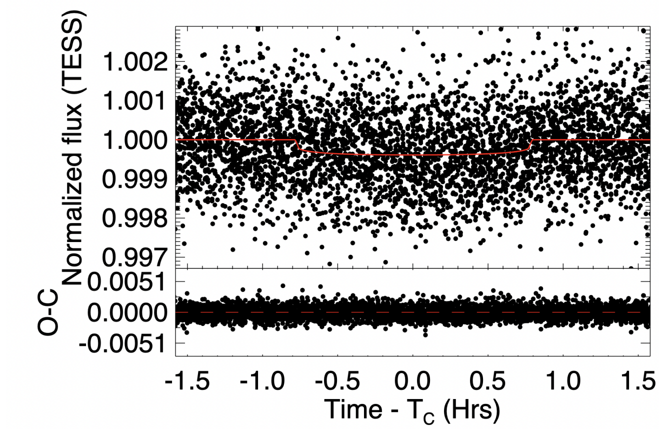

Figure 1. Image from transit mcmc file showing the dip in light received from the star caused by the transiting planet.

4.2. *SED Graph*

Figure 2 shows the brightness of the star plotted against it's wavelength. The graph shows both the peak wavelength of light emitted by the star and shows the quality of the fit. The peak wavelength is approximately 600 nanometers (0.6 microns). This means that the star is a yellow-green colour, much like our sun. The fit quality is assured by the fact that the error bars lie directly on top of the data points.

4.3. *MIST Graph*

The MIST model of the star's evolution, shown in 3, reveals that the star is on the main sequence and has a long way to go before exhausting it's hydrogen fuel and becoming a red giant.

4.4. *Chain Graph*

Figure 4 shows the quality of the fit as all the different chain links converge onto a common thread, creating the horizontal line after the vertical black line.

4.5. *Table 3*

The table represents the data derived from the EXOFAST fit. It encompasses stellar and planetary parameters precise to a degree not yet achieved for this system. It characterizes a super-earth orbiting a solar-type star.

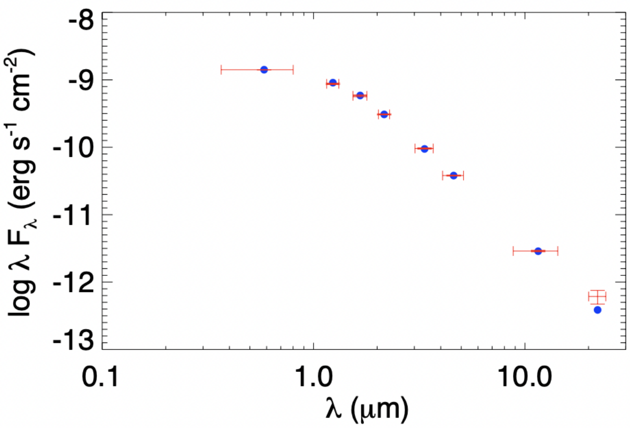

Figure 2. Image from sed mcmc file showing the calibration between the model and the data

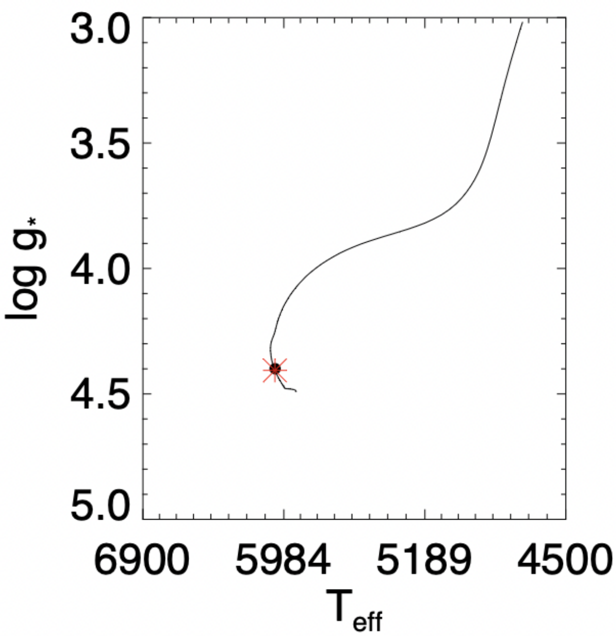

Figure 3. Image of mcmc MIST graph, showing where the star is in it's evolution.

Table 1. Median values and 68% confidence interval for 253990973., created using EXOFASTv2 commit number bba2fcf5

Parameter	Units	Values
Stellar Parameters:		
M_*	Mass ($M_\odot$)	$1.097^{+0.076}_{-0.068}$
R_*	Radius ($R_\odot$)	$1.144^{+0.043}_{-0.038}$
$R_{*,SED}$	Radius[1] ($R_\odot$)	$1.101^{+0.014}_{-0.012}$
L_*	Luminosity ($L_\odot$)	$1.452^{+0.095}_{-0.088}$
F_{Bol}	Bolometric Flux (cgs)	$0.00000000257 \pm 0.00000000016$
ρ_*	Density (cgs)	$1.04^{+0.13}_{-0.14}$
$\log g$	Surface gravity (cgs)	$4.363^{+0.041}_{-0.050}$
$T_{\rm eff}$	Effective Temperature (K)	5920^{+140}_{-120}
$T_{\rm eff,SED}$	Effective Temperature[1] (K)	6030^{+120}_{-110}
$[{\rm Fe/H}]$	Metallicity (dex)	$0.16^{+0.15}_{-0.12}$
$[{\rm Fe/H}]_0$	Initial Metallicity[2]	$0.17^{+0.12}_{-0.10}$
Age	Age (Gyr)	$3.8^{+3.5}_{-2.4}$
EEP	Equal Evolutionary Phase[3]	365^{+42}_{-37}
A_V	V-band extinction (mag)	$0.347^{+0.081}_{-0.076}$
σ_{SED}	SED photometry error scaling	$1.43^{+0.55}_{-0.42}$
ϖ	Parallax (mas)	$7.438^{+0.040}_{-0.045}$
d	Distance (pc)	$134.44^{+0.81}_{-0.72}$
Planetary Parameters:		b
P	Period (days)	$0.540959^{+0.000079}_{-0.00016}$
R_P	Radius ($R_{\rm J}$)	$0.207^{+0.010}_{-0.011}$
M_P	Mass[4] ($M_{\rm J}$)	$0.0211^{+0.0071}_{-0.0051}$
T_C	Time of conjunction[5] ($\rm BJD_{TDB}$)	$2458654.2534^{+0.0065}_{-0.0040}$
T_T	Time of minimum projected separation[6] ($\rm BJD_{TDB}$)	$2458654.2533^{+0.0066}_{-0.0034}$
T_0	Optimal conjunction Time[7] ($\rm BJD_{TDB}$)	$2458675.3508^{+0.0015}_{-0.0017}$
a	Semi-major axis (AU)	$0.01340^{+0.00030}_{-0.00028}$
i	Inclination (Degrees)	$82.6^{+4.9}_{-4.5}$
e	Eccentricity	$0.20^{+0.26}_{-0.13}$
ω_*	Argument of Periastron (Degrees)	-190^{+190}_{-130}
T_{eq}	Equilibrium temperature[8] (K)	2640^{+46}_{-45}
$\tau_{\rm circ}$	Tidal circularization timescale (Gyr)	$0.0072^{+0.0058}_{-0.0062}$
K	RV semi-amplitude[4] (m/s)	$5.2^{+1.6}_{-1.2}$
R_P/R_*	Radius of planet in stellar radii	$0.01864^{+0.00063}_{-0.00072}$
a/R_*	Semi-major axis in stellar radii	$2.52^{+0.10}_{-0.12}$
δ	$(R_P/R_*)^2$	$0.000348^{+0.000024}_{-0.000026}$
$\delta_{\rm TESS}$	Transit depth in TESS (fraction)	$0.000399^{+0.000028}_{-0.000027}$

Table 1 continued

Table 1 *(continued)*

Parameter	Units	Values
τ	Ingress/egress transit duration (days)	$0.00134^{+0.00025}_{-0.00012}$
T_{14}	Total transit duration (days)	$0.0639^{+0.0029}_{-0.0026}$
T_{FWHM}	FWHM transit duration (days)	$0.0625^{+0.0029}_{-0.0026}$
b	Transit Impact parameter	0.29 ± 0.19
b_S	Eclipse impact parameter	$0.30^{+0.18}_{-0.19}$
τ_S	Ingress/egress eclipse duration (days)	0.00146 ± 0.00023
$T_{S,14}$	Total eclipse duration (days)	$0.0669^{+0.0090}_{-0.0086}$
$T_{S,FWHM}$	FWHM eclipse duration (days)	$0.0654^{+0.0089}_{-0.0085}$
$\delta_{S,2.5\mu m}$	Blackbody eclipse depth at 2.5μm (ppm)	$72.7^{+5.9}_{-6.2}$
$\delta_{S,5.0\mu m}$	Blackbody eclipse depth at 5.0μm (ppm)	$110.0^{+8.4}_{-8.7}$
$\delta_{S,7.5\mu m}$	Blackbody eclipse depth at 7.5μm (ppm)	$124.4^{+9.4}_{-9.6}$
ρ_P	Density[4] (cgs)	$2.87^{+1.1}_{-0.63}$
$logg_P$	Surface gravity[4]	$3.08^{+0.13}_{-0.10}$
Θ	Safronov Number	$0.00250^{+0.00077}_{-0.00059}$
$\langle F \rangle$	Incident Flux (10^9 erg s^{-1} cm^{-2})	$10.3^{+1.1}_{-1.4}$
T_P	Time of Periastron (BJD$_{\rm TDB}$)	$2458654.237^{+0.099}_{-0.065}$
T_S	Time of eclipse (BJD$_{\rm TDB}$)	$2458654.529^{+0.13}_{-0.088}$
T_A	Time of Ascending Node (BJD$_{\rm TDB}$)	$2458654.133^{+0.053}_{-0.049}$
T_D	Time of Descending Node (BJD$_{\rm TDB}$)	$2458654.384^{+0.073}_{-0.041}$
V_c/V_e		$0.945^{+0.053}_{-0.074}$
$((1-R_P/R_*)^2-b^2)^{1/2}$		$0.978^{+0.036}_{-0.078}$
$sign$		$0.56^{+0.24}_{-0.30}$
$e\cos\omega_*$		$0.01^{+0.37}_{-0.25}$
$e\sin\omega_*$		$0.024^{+0.073}_{-0.079}$
$M_P \sin i$	Minimum mass[4] ($M_{\rm J}$)	$0.0208^{+0.0070}_{-0.0050}$
M_P/M_*	Mass ratio[4]	$0.0000185^{+0.0000055}_{-0.0000046}$
d/R_*	Separation at mid transit	$2.29^{+0.21}_{-0.31}$
P_T	A priori non-grazing transit prob	$0.428^{+0.066}_{-0.036}$
$P_{T,G}$	A priori transit prob	$0.445^{+0.069}_{-0.038}$
P_S	A priori non-grazing eclipse prob	$0.394^{+0.12}_{-0.033}$
$P_{S,G}$	A priori eclipse prob	$0.409^{+0.13}_{-0.034}$
Wavelength Parameters:		TESS
u_1	linear limb-darkening coeff	$0.296^{+0.053}_{-0.050}$
u_2	quadratic limb-darkening coeff	0.288 ± 0.047
Transit Parameters:		TESS UT 2000-01-01 (TESS)
σ^2	Added Variance	$0.0000001395^{+0.0000000099}_{-0.0000000093}$
F_0	Baseline flux	$1.0000595^{+0.0000072}_{-0.0000079}$

Table 1 continued

Table 1 *(continued)*

Parameter	Units	Values

See Table 3 in Eastman et al. (2019) for a detailed description of all parameters

[1] This value ignores the systematic error and is for reference only

[2] The metallicity of the star at birth

[3] Corresponds to static points in a star's evolutionary history. See §2 in Dotter (2016).

[4] Uses measured radius and estimated mass from Chen & Kipping (2017)

[5] Time of conjunction is commonly reported as the "transit time"

[6] Time of minimum projected separation is a more correct "transit time"

[7] Optimal time of conjunction minimizes the covariance between T_C and Period

[8] Assumes no albedo and perfect redistribution

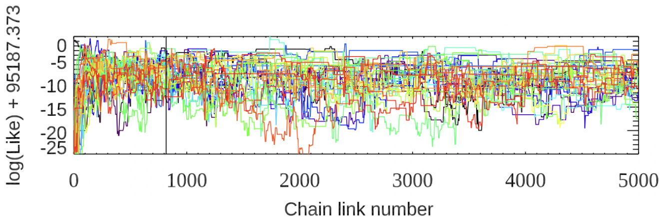

Figure 4. Image of chain graph, showing how all the chains converge to show that my result is probable.

5. DISCUSSION

5.1. *Tidal Locking*

I picked this planet because I expected it to be tidally locked. It has an extremely short period (0.540959 days) and thus was very likely to be tidally locked. After the fit, I determined that the planet is tidally locked through the following calculation:

If twice the lower bound of the uncertainty for the eccentricity is greater than the value presented then one can assume the orbit is circular, and with its distance from the star I can conclude that the planet is tidally locked.

1.

$$0.20 - 2 \times 0.13 = -0.6 \tag{1}$$

So since the result is negative, the planet is confirmed to be tidally locked.

5.2. *Eccentricity*

The eccentricity of the planet's orbit is listed as 0.2, even though the circularization time is less than the age of the star. Therefore the orbit should be circular (and have an eccentricity of zero). However, as discussed in section 5.1, this value is consistent with a circular orbit as the error is so large.

5.3. *Temperature*

Also, this planet has an equilibrium temperature, T_{eq}, of 2640 K. This is a temperature similar to that of some of the cooler stars in the universe, and this is because the semi-major axis is 0.01340 AU. This corresponds to a distance of 2,004,611.47 km, which is less than the distance from the Earth to Mars. This temperature is well above the melting point of stone.

5.4. *Companion*

The star has a smaller companion that decreases the transit depth by adding its light to that of the light of the main star. It is 3.1 magnitudes above the brightness of my star, and below I calculated the actual fraction of brightness that represents.

$$b_1 = \text{brightness of companion} \tag{2}$$
$$b_2 = \text{brightness of main star} \tag{3}$$

4.

$$\frac{b_2}{b_1} = \left(100^{0.2}\right)^{(m_1 - m_2)} \tag{4}$$
$$= \left(100^{0.2}\right)^{(3.1)} \tag{5}$$
$$= \left(100^{0.62}\right) \tag{6}$$
$$= 17.37800829 \tag{7}$$
$$= 17 \tag{8}$$

Therefore the companion star is 17 times less bright than the main star. That makes the transit dimmer by a factor of 1/17.

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This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

This paper makes use of EXOFAST (Eastman et al. 2013) as provided by the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

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