



Discovery and Characterization of an Eccentric, Warm Saturn Transiting the Solar Analog TOI-4994*

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Abstract

We present the detection and characterization of TOI-4994b (TIC 277128619b), a warm Saturn-sized planet discovered by the NASA Transiting Exoplanet Survey Satellite. TOI-4994b transits a G-type star ($V = 12.6$ mag) with a mass, radius, and effective temperature of $M_* = 1.005^{+0.064}_{-0.061} M_\odot$, $R_* = 1.055^{+0.040}_{-0.037} R_\odot$, and $T_{\text{eff}} = 5640 \pm 110$ K. We obtained follow-up ground-based photometry from the Las Cumbres Observatory and the Antarctic Search for Transiting Exoplanets telescopes, and we confirmed the planetary nature of TOI-4994b with multiple radial velocity observations from the Planet Finder Spectrograph, CHIRON, High Accuracy Radial velocity Planet Searcher, Fiber-fed Extended Range Optical Spectrograph, and CORALIE instruments. From a global fit to the photometry and radial velocities, we determine that TOI-4994b is in a 21.5 day eccentric orbit ($e = 0.32 \pm 0.04$) and has a mass of $M_p = 0.280^{+0.037}_{-0.034} M_J$, a radius of $R_p = 0.762^{+0.030}_{-0.027} R_J$, and a Saturn-like bulk density of $\rho_p = 0.78^{+0.16}_{-0.14} \text{ g cm}^{-3}$. We find that TOI-4994 is a potentially viable candidate for follow-up stellar

* This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.



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obliquity measurements. TOI-4994b joins the small sample of warm Saturn analogs and thus sheds light on our understanding of these rare and unique worlds.

Unified Astronomy Thesaurus concepts: [Exoplanets \(498\)](#); [Extrasolar gaseous planets \(2172\)](#)

1. Introduction

The number of known giant exoplanets has vastly expanded since the discovery of the first transiting giant planet (D. Charbonneau et al. 2000; G. W. Henry et al. 2000) with the advent of many wide-field transit and radial velocity (RV) surveys (e.g., G. Á. Bakos et al. 2007, 2013; D. L. Pollacco et al. 2006; J. Pepper et al. 2007; W. J. Borucki et al. 2010). However, despite the thousands of giant planet discoveries brought about by these dedicated surveys, there are still many open questions regarding the formation mechanisms, composition, and evolution of these planets. One such longstanding problem in planetary astrophysics is whether close-in giant planets form in situ or instead form at larger orbital separations beyond the snow line and subsequently migrate inward through interactions with the protoplanetary disk (e.g., W. Kley & R. P. Nelson 2012; R. P. Nelson 2018). In addition, the migration pathways of these planets are poorly understood (see, e.g., J. N. Winn & D. C. Fabrycky (2015), R. I. Dawson & J. A. Johnson (2018); J. Schulte et al. 2024).

Transiting giant planets offer important clues to some of these problems, as they are comparatively easier to detect than small planets and are rich targets for characterization. First, they enable precise measurements of masses, radii, and orbital properties, providing valuable insights into their bulk composition and interior structure (J. J. Fortney et al. 2007; J. J. Fortney & N. Nettelmann 2010). The study of these objects refines and contextualizes our knowledge of the giant planets in our solar system, while allowing us to explore the extreme physics of other types of planets that are not present within it. The relatively larger scale heights of giant planets (i.e., planet-to-star radius ratio) make them excellent targets for follow-up atmospheric characterization, providing clues about their heavy-element mass, interior structure, and formation histories (N. Madhusudan et al. 2014; D. P. Thorngren et al. 2016). These planets are also particularly well suited for measurements of the sky-projected spin-orbit angle with the Rossiter-McLaughlin (RM) effect or Doppler tomography (B. S. Gaudi & J. N. Winn 2007).

Warm giant planets, which have equilibrium temperatures below ~ 1000 K or orbital periods between 10 and 200 days ($a \gtrsim 0.1$ au), are uniquely interesting because, at their larger distances from their host stars, they are likely not subjected to the same physical processes that inflate the atmospheres of hot Jupiters (J. J. Fortney & N. Nettelmann 2010; A. Jordán et al. 2020; S. Müller & R. Helled 2023). Therefore, their observed properties are likely primordial and enable comparisons between planets at close distances from their host stars. However, the number of well-characterized warm transiting giants is still small, partly because the transit and RV methods are both biased toward planets on shorter periods. Additionally, most of the warm giants discovered from space missions like Kepler and CoRoT orbit fainter stars that are not especially amenable to follow-up observations. In fact, as of 2024 August 9, warm giants comprise only 17% (180 planets) of all known giants.³⁰

The NASA Transiting Exoplanet Survey Satellite (TESS; G. R. Ricker et al. 2015) has been tremendously successful at finding all kinds of exoplanets, and it is expected to find over 250

giant planets with 2 minute cadence (T. Barclay et al. 2018). In this paper, we present the discovery of the warm Saturn TOI-4994b, which orbits a moderately bright ($V = 12.6$ mag) G-type star on an eccentric 21.5 day period orbit, discovered with data from TESS. The signals were followed up and confirmed as planetary with a suite of ground-based photometry from Las Cumbres Observatory (T. M. Brown et al. 2013) and the ASTEP-Antarctica observatory (J.-B. Daban et al. 2010), as well as RV observations from multiple spectrographs. The unique properties of Saturn analogs along with their relative rarity make them valuable laboratories to test and refine theories of planet formation. This paper is structured as follows. In Section 2, we provide confirmation of the planetary nature of TOI-4994b from our photometric and spectroscopic observations. In Section 3, we present our analysis of the data. In Section 4, we present our results and the properties of the planet in the context of the known exoplanet population, and we finally conclude in Section 5.

2. Observations

TOI-4994 (TIC 277128619) is a moderately bright ($V = 12.6$ mag) G-type star located at R.A. = $18^{\text{h}}52^{\text{m}}31^{\text{s}}.81$ and decl. = $-78^{\circ}26'03''95$ at a distance of 330.9 ± 2.45 pc (see Table 1 and Section 3 for more on the properties of the host). A transit-like signal with a period of 21.5 days was first detected in Sector 12 of TESS and subsequently confirmed with follow-up photometry from the ground. We describe these and the RV observations in detail in the following subsections.

2.1. TESS Photometry

Since its launch in 2018, the TESS mission has found thousands of transiting exoplanet candidates around the nearest and brightest dwarf stars. TESS has four cameras that survey 95% of the sky. Currently, over 400 exoplanets have been confirmed or statistically validated, and we expect many more to follow.

TOI-4994b (TIC 277128619b) was first observed in Sectors 12 and 13 in 2019 June–July by Camera 3 at 30 minute cadence, and then again in Sectors 27 (2020 July) and 39 (2021 June) at 10 minute cadence, and finally in Sectors 66 and 67 in 2023 June–July at 2 minute cadence (M. C. Stumpe et al. 2012, 2014; J. C. Smith et al. 2012). A total of 11 TESS transits were observed across these sectors. The target will also be reobserved in 2025 in June and July. Data from all six sectors were used in our analysis.

The TESS data were processed and reduced with the NASA Science Processing Operations Center pipeline (J. M. Jenkins et al. 2016; D. A. Caldwell et al. 2020), which searches for and identifies transit-like signals in the data. A threshold-crossing event was detected at 21.5 days using a Box Least Squares algorithm, identifying the target as a TESS Object of Interest. The light curves were then downloaded using the `lightcurve` package (Lightcurve Collaboration et al. 2018), which retrieves data from the Barbara A. Mikulski Archive for Space Telescopes.³¹ Finally, the light curves were flattened

³⁰ Data from the NASA Exoplanet Archive.

³¹ <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

Table 1
Stellar Properties from the Literature

Parameter Identifiers	Value	Source
TIC ID	277128619	1
TOI	4994	1
2MASS	J18523181-7826041	1
Gaia DR3	6364463103935391232	1
Coordinates and Proper Motion		
R.A. (RA)	18:52:31.81	2
decl. (Dec)	−78:26:03.95	2
μ_{α} (mas yr ^{−1})	0.897 ± 0.009	2
μ_{δ} (mas yr ^{−1})	9.9 ± 0.01	2
Gaia Parallax (mas)	3.022 ^{+0.022} _{−0.023}	2
Distance (pc)	330.9 ^{+2.5} _{−2.4}	3
Broadband Magnitudes		
Gaia <i>G</i> mag.	12.4792 ± 0.0001	2
Gaia <i>G</i> _{BP} mag.	12.913 ± 0.001	2
Gaia <i>G</i> _{RP} mag.	11.9044 ± 0.0007	2
TESS mag	11.954 ± 0.006	4
2MASS <i>J</i> mag.	11.221 ± 0.021	5
2MASS <i>H</i> mag.	10.85 ± 0.022	5
2MASS <i>K</i> _s mag.	10.797 ± 0.022	5
WISE 1 mag.	10.734 ± 0.023	6
WISE 2 mag.	10.793 ± 0.021	6
WISE 3 mag.	10.684 ± 0.068	6

References: SIMBAD Astronomical Database,¹ Gaia Collaboration et al. (2023),² this work,³ TIC-v8.2 (K. G. Stassun et al. 2019),⁴ R. M. Cutri et al. (2003),⁵ and N. Zacharias et al. (2017).⁶

using `keplersplinev2`³² (A. Vanderburg & J. A. Johnson 2014), which removes any out-of-transit variability due to stellar activity. The time series and phase-folded TESS transit light curves are shown in Figures 1 and 2.

2.2. Ground-based Photometry

The TESS pixel scale is $\sim 21''$ pixel^{−1}, and photometric apertures typically extend out to roughly 1 arcmin, generally causing multiple stars to blend in the photometric aperture. To determine the true source of the TESS detection, we acquired ground-based time-series follow-up photometry of the field around TOI-4994 as part of the TESS Follow-up Observing Program (K. Collins 2019).³³ We used the TESS Transit Finder, which is a customized version of the *Tapir* software package (E. Jensen 2013), to schedule our transit observations.

2.2.1. LCOGT

Follow-up light-curve observations were taken with the Las Cumbres Observatory Global Telescope (LCOGT; T. M. Brown et al. 2013) 1 m network nodes at the South African Astronomical Observatory (SAAO) in Cape Town, South Africa, and Cerro Tololo Interamerican Observatory (CTIO) in Chile. A full transit was observed simultaneously in *g'* and *i'* bands on 2023 July 11 from SAAO, and an ingress observation was conducted simultaneously in *g'* and *i'* bands on 2023 May 8 from CTIO. The 1 m telescopes are equipped with 4096 × 4096 SINISTRO cameras with an image scale of 0.389'' per pixel, resulting in a field of view of 26' × 26'. The images were calibrated by the standard LCOGT BANZAI pipeline

³² <https://github.com/avanderburg/keplersplinev2>

³³ <https://tess.mit.edu/followup>

(C. McCully et al. 2018), and differential photometric data were extracted using *AstroImageJ* (K. A. Collins et al. 2017). Circular photometric apertures with a 4.3'' radius were used, effectively excluding most of the flux from the nearest known neighbor in the Gaia DR3 catalog, which is 6'' west of TOI-4994 and is 6.6 magnitudes fainter in the TESS band. The light-curve data are included in the global modeling described in Section 3, and the phase-folded transits are shown in Figure 3.

2.2.2. ASTEP-ANTARCTICA

We obtained follow-up photometric observations of TOI-4994 with the Antarctic Search for Transiting Exoplanets (ASTEP) telescope. ASTEP is a 0.4 m telescope located at Concordia Station in Antarctica (T. Guillot et al. 2015; D. Mékarnia et al. 2016). It is equipped with two back-illuminated cameras operating in the *B*+*V* bands, similar to Gaia-*B* (FLI Kepler KL400 sCMOS camera, 2048 × 2048 pixels), and in a red band close to the Gaia-*R* band (Andor iKon-L 936 CCD camera, 2048 × 2048 pixels). These cameras have an image scale of 1.05 and 1.30 pixel^{−1}, respectively, resulting in corrected fields of view of 36 × 36 and 44 × 44 arcmin² (F.-X. Schmider et al. 2022). The data are processed on-site using IDL (D. Mékarnia et al. 2016) and Python aperture photometry pipelines (G. Dransfield et al. 2022).

Four observations of TOI-4994 were carried out with ASTEP, all under good weather conditions. A full transit of TOI-4994b was observed on UT 2022 August 23 in the *R* band and on UT 2023 May 8 in the *B* and *R* bands, while two egress observations were observed on UT 2023 March 26 and on UT 2023 May 29, both in the *B* and *R* bands. The phase-folded transits are shown in Figure 3.

2.3. Spectroscopic Observations

We obtained follow-up RV observations from multiple spectrographs to constrain the mass and orbit of TOI-4994b, which we describe in detail below. To assess whether the star is magnetically active, we calculated its chromospheric activity index, R'_{HK} , which is based on the flux emitted by Ca II H and K lines. The R'_{HK} index is the fraction of the star's bolometric luminosity emitted in these lines through magnetic activity. Using the empirical NUV- R'_{HK} relations from K. Findeisen et al. (2011), we obtained $\log R'_{\text{HK}} = -5.06 \pm 0.05$, which is near the minimum value of the chromospheric activity index for stars with solar metallicity of $\log R'_{\text{HK}} = -5.08$. We therefore treat TOI-4994 as an inactive star. All the RV data sets are shown as a function of time and phase-folded on the best-fit period in Figures 4 and 5 and listed in the Appendix A.

2.3.1. PFS

We collected 15 RV measurements of TOI-4994 between UT 2023 July 28 and UT 2023 September 25 with the Carnegie Planet Finder Spectrograph (PFS; J. D. Crane et al. 2006, 2008, 2010). PFS is a high-precision echelle spectrograph attached to the 6.5 m Magellan Clay telescope at Las Campanas Observatory in Chile. It has a spectral resolution of 130,000 and covers the 390–734 nm spectral window. Wavelength calibration is carried out using an iodine absorption cell, which also allows for characterization of the instrumental profile. Spectra were reduced using the standard

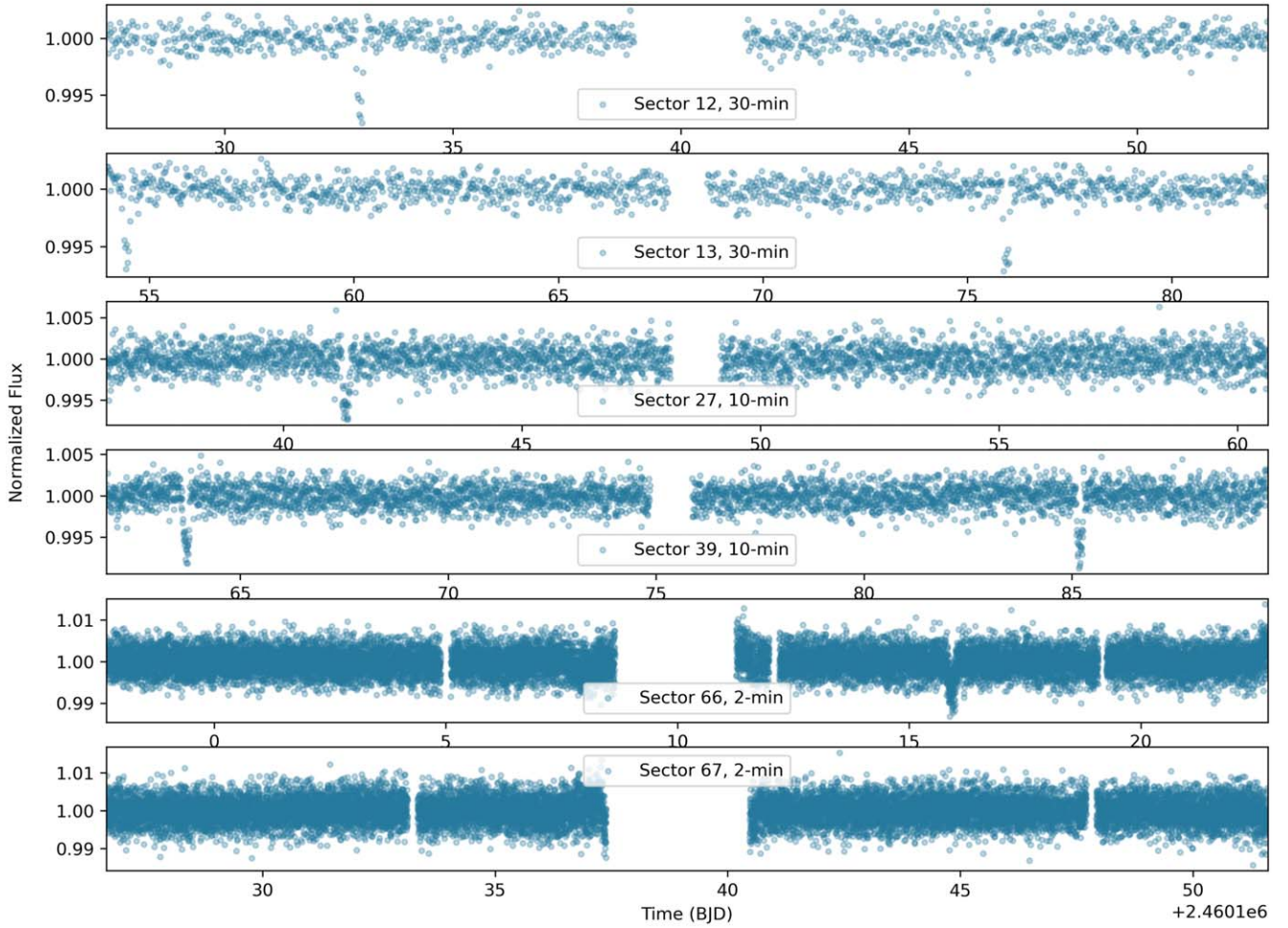


Figure 1. Time-series photometry of all six TESS sectors used in our analysis.

PFS reduction pipeline (R. P. Butler et al. 1996; J. D. Crane et al. 2006), and RV measurements were extracted using a custom IDL pipeline.

2.3.2. CHIRON

We obtained 15 spectra of TOI-4994 with the CHIRON high-resolution spectrograph on the SMARTS 1.5 m telescope located at CTIO in Chile. CHIRON is a fiber-fed echelle spectrograph with a resolving power of $R = 80,000$ over the wavelength range 4100–8700 Å (A. Tokovinin et al. 2013). The observations were taken between UT 2022 August 28 and October 24. Wavelength calibrations are provided by bracketing Thorium–Argon (Th–Ar) arc lamp exposures. Relative velocities were measured from each spectrum by deriving their stellar line broadening kernels via a least-squares deconvolution analysis (described in G. Zhou et al. 2016).

2.3.3. HARPS

We obtained a total of 10 RV measurements from the High Accuracy Radial velocity Planet Searcher (HARPS; M. Mayor et al. 2003) on the 3.6 m European Southern Observatory (ESO) telescope in La Silla Observatory, Chile. HARPS is a high-resolution spectrograph with a precision on the order of 1 m s^{-1} , a resolving power of 115,000, and a wavelength range of 378–691 nm. The spectra and radial velocities were reduced

with the HARPS dedicated pipeline. The HARPS observations of our target were taken by two independent teams and therefore reduced with different methodologies. We label these HARPS-1 and HARPS-2 to distinguish them. In Figure 5, we plot only the most precise RV data from PFS and HARPS to better highlight the best-fit RV model.

2.3.4. CORALIE

TOI-4994 was observed by the CORALIE fiber-fed high-resolution echelle spectrograph located at the Swiss 1.2 m Leonhard Euler Telescope at ESO's La Silla Observatory (S. Udry et al. 2000; D. Queloz et al. 2001). It has a spectral resolution of 60,000 and a wavelength range of 390–680 nm. A total of seven RV observations of TOI-4994 were collected between UT 2022 April 11 and September 23. The observations have exposure times of 1800 s and a signal-to-noise ratio (S/N) ranging between 25 and 50 measured at 550 nm. The S/N variations are due to the different observing conditions. The RVs were obtained by cross-correlating each spectrum against a binary mask corresponding to the stellar type G2 (e.g., F. Pepe et al. 2002). The resulting product is a cross-correlation function (CCF) from which the RV is measured as well as several other indicators, such as the FWHM of the CCF, the bisector inverse slope, and the contrast of the CCF. Additional indexes such as H_α and Ca indexes are also derived from each spectrum.

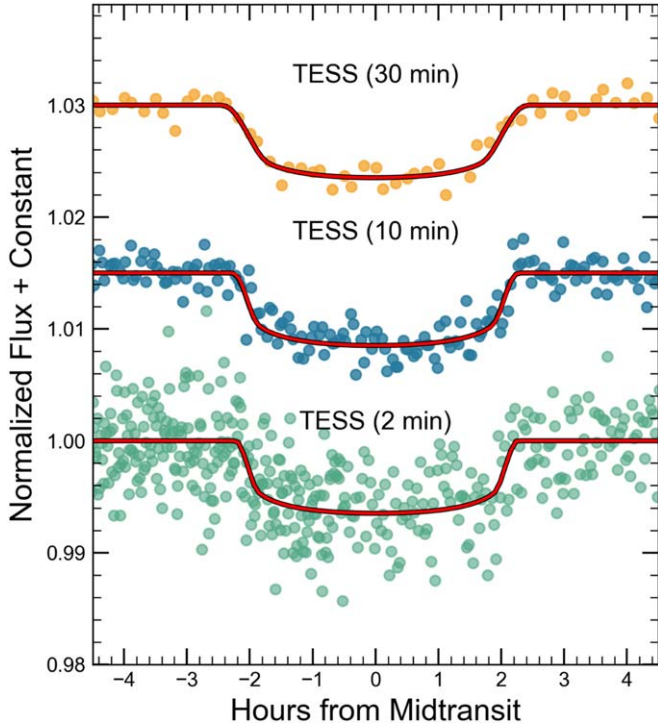


Figure 2. TESS light curves of TOI-4994 at 30 (top), 10 (middle), and 2 (bottom) minute cadences, combining six different sectors. The red lines show the best-fit EXOFASTv2 models, phase-folded on the orbital period.

2.3.5. FEROS

Additionally, we obtained a total of 20 RV observations with ESO's Fiber-fed Extended Range Optical Spectrograph (FEROS; A. Kaufer et al. 1999) located at La Silla Observatory in Chile. These observations were obtained in the context of the Warm gIaNTs with tEss collaboration, which focuses on the systematic discovery and characterization of transiting warm giant planets (e.g., R. Brahm et al. 2019; 2020, 2023; A. Jordán et al. 2020; M. Schlecker et al. 2020; M. J. Hobson et al. 2021, 2023; T. Trifonov et al. 2021; 2023; J. Eberhardt et al. 2023). FEROS has a spectral resolution of 48,000 and a wavelength coverage of 350–920 nm. Observations of TOI-4994 were taken between UT 2022 July 3 and UT 2023 September 7, with exposure times of 1200 s and S/Ns between 30 and 50 per resolution element. FEROS data were processed with the *ceres* pipeline (R. Brahm et al. 2017), which delivers precision radial velocities, bisector span measurements, and a rough estimation of the atmospheric stellar parameters.

2.4. High-resolution Imaging with SOAR

We obtained high-resolution speckle images of TOI-4994 to check that the signals originate from the target star and not from another nearby stellar companion that could contaminate the SED and affect the inferred transit depth. The star was observed with the speckle camera at the Southern Astrophysical Research (SOAR) 4.1 m telescope on UT 2022 August 18. The data reduction process and a thorough description of the SOAR-TESS survey can be found in A. Tokovinin (2018) and C. Ziegler et al. (2019). In Figure 6, we show the 5σ limit of companion detection, and the inset shows the speckle autocorrelation function. From this observation, we can exclude the presence of any stellar companion within about 4.5 magnitudes of the brightness of TOI-4994 and an angular

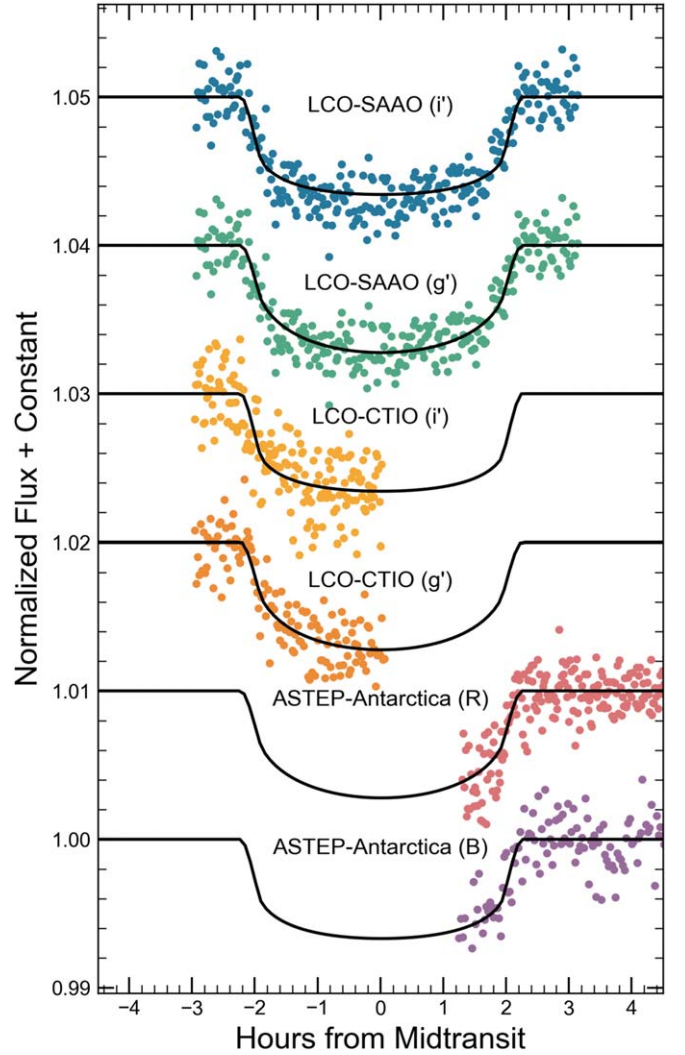


Figure 3. Light curves of TOI-4994 from the LCOGT and ASTEP-Antarctica ground-based observatories.

separation between $0''.25$ and $2''$ and within about 5 magnitudes for larger separations.

3. Global Analysis

To constrain the stellar and planetary parameters of the system, we conducted a global fit of all our data using the publicly available exoplanet modeling suite EXOFASTv2 (J. Eastman et al. 2013; J. Eastman 2017; J. D. Eastman et al. 2019). The physical properties of the host star were determined from a combination of the spectral energy distribution (SED) fit, as well as spectroscopic priors from our CHIRON data (including an initial estimate of the effective temperature and $\log g$), a parallax prior from Gaia DR3 (Gaia Collaboration et al. 2023), and an upper bound on the extinction from galactic dust maps. For the SED fit, we incorporated available photometry from GaiaG, G_{BP} , and G_{RP} bands, 2MASS J , H , and K magnitudes, and WISE W_1 – W_4 magnitudes (see Table 1 for these values). R. L. Kurucz (1992) atmosphere model was fit to all the available fluxes. As priors to the SED and global fit, we adopted a parallax of $\mu = 3.022^{+0.022}_{-0.023}$ mas from Gaia EDR3 (corrected as per L. Lindegren et al. 2021). We set an upper limit on the maximum line-of-sight visual extinction A_V of 0.350 from the

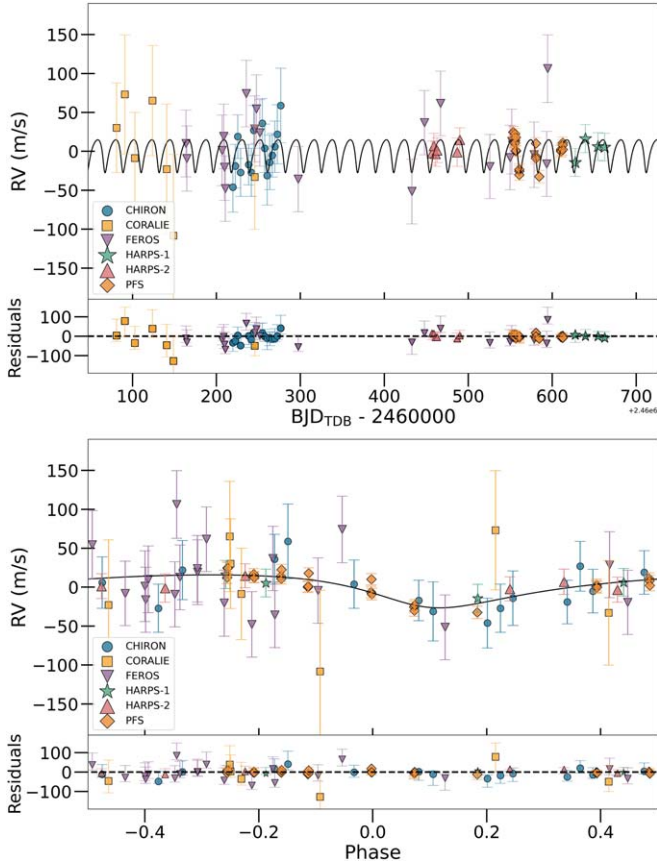


Figure 4. RV measurements of TOI-4994 (top) phase-folded on the orbital period (bottom). The black lines show the best-fit EXOFASTv2 models, with the residuals shown below the RV curves.

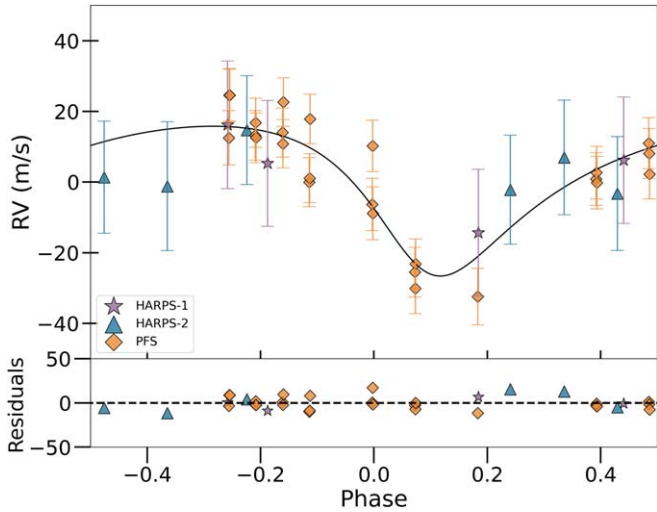


Figure 5. Phase-folded radial velocities from PFS (golden diamonds) and HARPS (purple stars and blue triangles) only, with residuals plotted below.

D. J. Schlegel et al. (1998) extinction maps. We used a prior on $[\text{Fe}/\text{H}]$ of 0.11 ± 0.09 dex, which is the median metallicity of all our spectra from CHIRON.

Within this SED fit, we use the MESA Isochrones and Stellar Tracks (MIST) stellar evolution models (A. Dotter 2016). Figure 7 illustrates the resulting SED fit, while the MIST evolutionary track is shown in Figure 8. The inferred stellar parameters are summarized in Table 2.

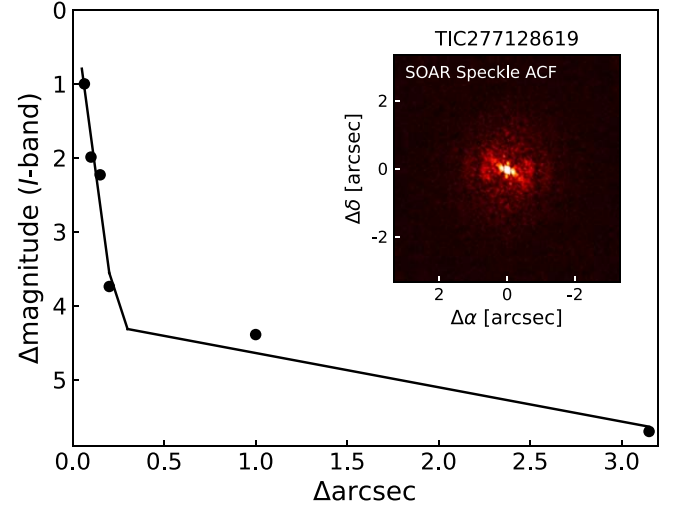


Figure 6. *I* band speckle image and sensitivity curve for TOI-4994 from the SOAR telescope.

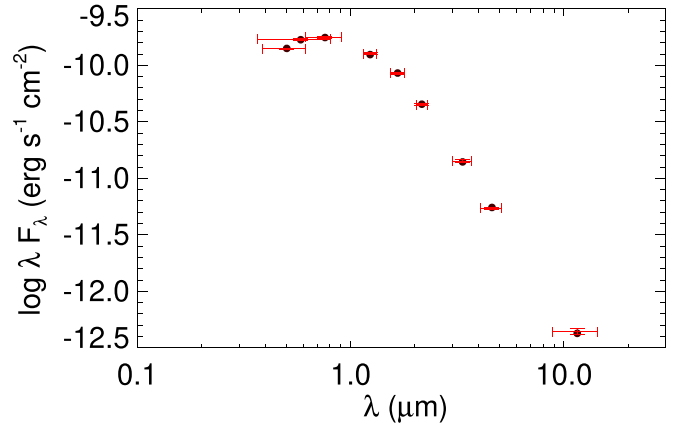


Figure 7. SED fit for TOI-4994. The horizontal error bars correspond to the bandwidth of each filter, while the error bars in flux are the measurement uncertainties. The black points are the modeled broadband averages.

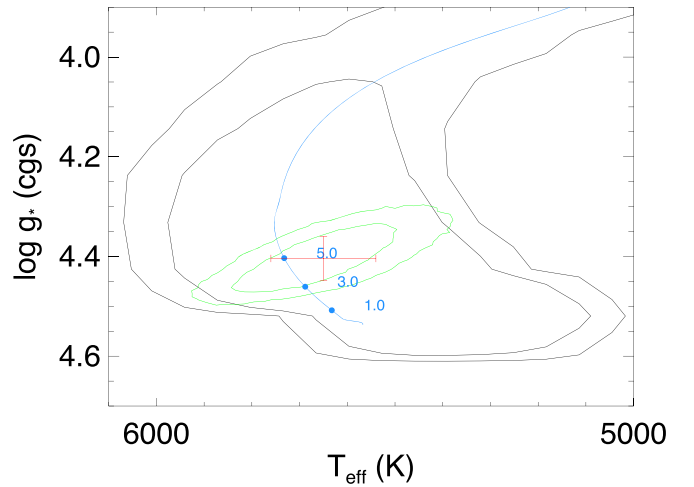


Figure 8. Evolutionary track and present evolutionary stage of TOI-4994 based on the best-fit MIST model. The blue line is the MIST track and the black contours represent the 1σ and 2σ constraints on the current temperature and surface gravity from the MIST isochrone, while the green contours show the 1σ and 2σ constraints on T_{eff} and $\log g_*$ from the EXOFASTv2 fit and observations of the system. The red cross indicates the median value and confidence intervals.

Table 2
Median Values and 68% Confidence Interval for Global Model of TOI-4994

Parameter	Units	Values
M_*	Mass ($M_\odot$).....	$1.005^{+0.064}_{-0.061}$
R_*	Radius ($R_\odot$)....	$1.055^{+0.040}_{-0.037}$
L_*	Luminosity ($L_\odot$)	$1.020^{+0.041}_{-0.052}$
F_{Bol}	Bolometric Flux (cgs).....	$(2.98^{+0.11}_{-0.15}) \times 10^{-10}$
ρ_*	Density (cgs).....	$1.21^{+0.17}_{-0.16}$
$\log g$	Surface gravity (cgs).....	$4.393^{+0.045}_{-0.046}$
T_{eff}	Effective Temperature (K).....	5640 ± 110
[Fe/H]	Metallicity (dex).....	$0.165^{+0.083}_{-0.084}$
[Fe/H] ₀	Initial Metallicity ^a	$0.176^{+0.079}_{-0.080}$
Age.....	Age (Gyr).....	$6.3^{+4.2}_{-3.8}$
EEP.....	Equal Evolutionary Phase ^b	380^{+31}_{-41}
A_V	V band extinction (mag).....	$0.295^{+0.041}_{-0.073}$
σ_{SED}	SED photometry error scaling	$0.73^{+0.31}_{-0.19}$
ϖ	Parallax (mas).....	$3.022^{+0.022}_{-0.023}$
d	Distance (pc).....	$330.9^{+2.5}_{-2.4}$

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

^a The metallicity of the star at birth.

^b Corresponds to static points in a star's evolutionary history. See Section 2 in A. Dotter (2016).

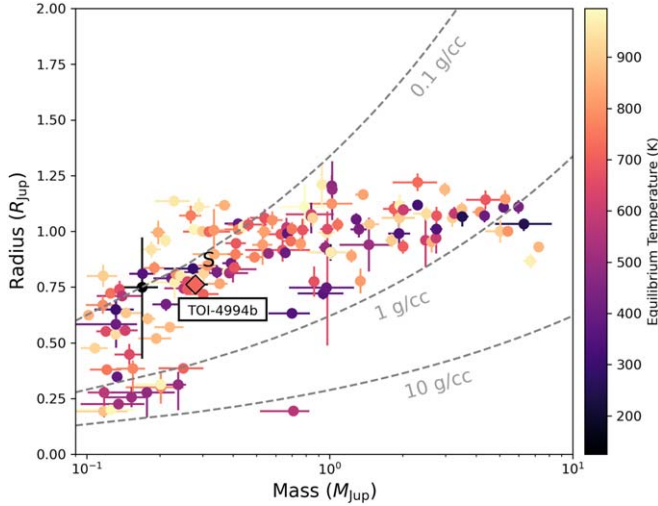


Figure 9. Mass–radius diagram of all warm giants (planet masses between $0.1 \leq M_{\text{Jup}} \leq 10$ and temperatures below 1000 K). The gray dashed lines are lines of constant bulk density. TOI-4994b is represented by a diamond, and Saturn is overplotted for reference.

We infer a stellar mass of $M_* = 1.005^{+0.064}_{-0.061} M_\odot$, a radius of $R_* = 1.055^{+0.040}_{-0.037} R_\odot$, and an effective temperature of $T_{\text{eff}} = 5640 \pm 100$ K, making this host a middle-aged ($6.3^{+4.2}_{-3.8}$ Gyr) G5 dwarf (per the classifications by M. J. Pecaut & E. E. Mamajek 2013) and an almost identical solar twin. The star exhibits a slightly enhanced metallicity, however, with $[\text{Fe}/\text{H}] = 0.165^{+0.083}_{-0.084}$ dex. Using the empirical R'_{HK} –age relations by E. E. Mamajek & L. A. Hillenbrand (2008), we derived an age for the system of 7.8 ± 1.3 Gyr, which is consistent with the age from our SED fit. These relations also predict a stellar rotation period of 46.2 ± 3.1 days.

The planetary parameters were determined through a simultaneous global fit of the system, which combined the TESS and ground-based photometry and the six RV data sets described in Sections 2.1, 2.2, and 2.3. EXOFASTv2

determines the stellar and planetary parameters using a differential evolution Markov Chain Monte Carlo method (see J. Eastman et al. 2013 for further details). We adopted an initial guess on the ephemeris from an independent fit to the TESS light curves. The resulting planetary parameters are listed in Table 3. The corner plots from our analysis are shown in the Appendix in Figure A1.

4. Results and Discussion

From our global fit to the available photometry and RV data sets, we determined a planetary mass of $M_p = 0.280^{+0.037}_{-0.034} M_J$ (or $89.1 M_\oplus$), a radius of $R_p = 0.762^{+0.030}_{-0.027} R_J$ (or $8.55 R_\oplus$), and a bulk density of $\rho_p = 0.78^{+0.16}_{-0.14} \text{ g/cm}^3$. These properties are similar to those of Saturn, and given the planet's orbital period, it fits in with the population of warm Saturns. The number of well-characterized warm Saturns in the literature is still small. There are currently less than 20 planets between 0.8 and $1.1 M_{\text{Sat}}$ and with periods between 10 and 200 days that have directly measured masses and radii, making this object a valuable addition to this rare sample. Some of these include HD 89345b (V. Van Eylen et al. 2018), K2-287b (A. Jordán et al. 2020), K2-261b (M. C. Johnson et al. 2018), NGTS-11b (TOI-1847b; S. Gill et al. 2020), and K2-232b (R. Brahm et al. 2020).

Although the mass and radius of TOI-4994b are slightly too large to categorize it as a sub-Saturn (typically defined as planets with $4 < R_p/R_\oplus < 8$), it shares many characteristics with this population, described in detail by E. A. Petigura et al. (2017). Notably, TOI-4994b is a single planet (with no evidence of other companions in the system) and has an eccentric orbit ($e = 0.32^{+0.048}_{-0.047}$). Such high eccentricity and lack of observed companions (characteristic of the most massive sub-Saturns) may be evidence of past dynamical instability, as hypothesized by E. A. Petigura et al. (2017). In addition, TOI-4994b orbits a metal-rich star ($[\text{Fe}/\text{H}] = 0.165^{+0.083}_{-0.084}$ dex), like the majority of known sub-Saturns. Interestingly, E. A. Petigura et al. (2017) also found strong correlations between planet mass, eccentricity, and host star metallicity.

Table 3
Median Values and 68% Confidence Interval for Global Model of TOI-4994 b

Parameter	Description (Units)	Values
P	Period (days).....	21.491984 ± 0.000023
R_p	Radius (R_p).....	$0.762^{+0.030}_{-0.027}$
M_p	Mass (M_J).....	$0.280^{+0.037}_{-0.034}$
T_C	Time of conjunction ^b (BJD _{TDB}).....	$2459363.69480 \pm 0.00076$
T_T	Time of minimum projected separation ^c (BJD _{TDB}).....	$2459363.69484 \pm 0.00076$
T_0	Optimal conjunction time ^d (BJD _{TDB}).....	$2459965.47035^{+0.00042}_{-0.00041}$
a	Semimajor axis (AU)	$0.1515^{+0.0032}_{-0.0031}$
i	Inclination (Degrees)	$89.56^{+0.29}_{-0.32}$
e	Eccentricity	$0.319^{+0.048}_{-0.047}$
ω_*	Argument of periastron (Degrees)	$143.1^{+9.5}_{-10}$
T_{eq}	Equilibrium temperature ^e (K).....	$717.6^{+9.7}_{-10}$
τ_{circ}^a	Tidal circularization time-scale (Gyr).....	610^{+400}_{-260}
K	RV semi-amplitude (m/s).....	$21.6^{+2.3}_{-2.3}$
R_p/R_*	Radius of planet in stellar radii	$0.07424^{+0.00078}_{-0.00068}$
a/R_*	Semimajor axis in stellar radii	30.9 ± 1.4
δ	$(R_p/R_*)^2$	$0.00551^{+0.00012}_{-0.00010}$
δ_B	Transit depth in B (fraction)	$0.00829^{+0.00039}_{-0.00035}$
δ_R	Transit depth in R (fraction)	$0.00684^{+0.00025}_{-0.00023}$
δ_g	Transit depth in g' (fraction)	$0.00788^{+0.00026}_{-0.00024}$
$\delta_{i'}$	Transit depth in i' (fraction).....	0.00662 ± 0.00016
δ_{TESS}	Transit depth in TESS (fraction)	0.00657 ± 0.00013
δ_V	Transit depth in V (fraction)	$0.00708^{+0.00025}_{-0.00024}$
τ	Ingress/egress transit duration (days).....	$0.01319^{+0.0011}_{-0.00041}$
T_{14}	Total transit duration (days)	$0.1855^{+0.0013}_{-0.0011}$
T_{FWHM}	FWHM transit duration (days).....	$0.17213^{+0.00092}_{-0.00091}$
b	Transit Impact parameter	$0.18^{+0.14}_{-0.12}$
b_S	Eclipse impact parameter	$0.26^{+0.18}_{-0.17}$
τ_S	Ingress/egress eclipse duration (days).....	$0.0202^{+0.0024}_{-0.0019}$
$T_{S,14}$	Total eclipse duration (days).....	$0.265^{+0.029}_{-0.025}$
$T_{S,FWHM}$	FWHM eclipse duration (days).....	$0.245^{+0.028}_{-0.025}$
$\delta_{S,2.5\mu m}^\dagger$	Blackbody eclipse depth at $2.5\mu m$ (ppm).....	$3.22^{+0.39}_{-0.35}$
$\delta_{S,5.0\mu m}^\dagger$	Blackbody eclipse depth at $5.0\mu m$ (ppm).....	$67.8^{+4.5}_{-4.1}$
$\delta_{S,7.5\mu m}^\dagger$	Blackbody eclipse depth at $7.5\mu m$ (ppm).....	$165.5^{+8.4}_{-7.7}$
ρ_p	Density (cgs).....	$0.78^{+0.16}_{-0.14}$
$\log g_p$	Surface gravity	$3.077^{+0.069}_{-0.074}$
$\langle F \rangle$	Incident flux (10^9 erg s ⁻¹ cm ⁻²)	$0.0544^{+0.0029}_{-0.0031}$
T_p	Time of periastron (BJD _{TDB}).....	$2459343.85^{+0.38}_{-0.35}$
T_S	Time of eclipse (BJD _{TDB}).....	$2459370.99^{+0.72}_{-0.74}$
V_c/V_e		0.797 ± 0.039
$e \cos \omega_*$		$-0.250^{+0.053}_{-0.056}$
$e \sin \omega_*$		$0.189^{+0.048}_{-0.047}$

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

^a These values are predicted values from theory and not directly observed.

^b Time of conjunction is commonly reported as the “transit time.”

^c Time of minimum projected separation is a more correct “transit time.”

^d Optimal time of conjunction minimizes the covariance between T_C and period.

^e Assumes no albedo and perfect redistribution.

R. Fairnington et al. (2025, in preparation) identified a potential bimodality in the eccentricity distribution of warm, single sub-Saturns, noting a scarcity of moderately eccentric planets ($e = 0.2\text{--}0.5$). TOI-4994b is the third confirmed object in this range, and its properties suggest a history shaped by planet–planet scattering and a possible merger (E. A. Petigura et al. 2017; M. T. Brady et al. 2018; S. C. Millholland et al. 2022). If a merger were the origin history of this planet, it may have a high bulk metallicity, which could be probed with JWST. While TOI-4994b's eccentricity and orbital distance are inconsistent with high-eccentricity migration, additional RV follow-up to search for long-period nontransiting companions may provide additional insights into its formation history.

TOI-4994b has a relatively high equilibrium temperature of $717.6^{+9.7}_{-10}$ K, calculated using Equation 1 from B. M. S. Hansen & T. Barman (2007) within EXOFASTv2:

$$T_{eq} = T_{\text{eff}} \sqrt{\frac{R_{\star}}{2a}}, \quad (1)$$

and which assumes an albedo of zero and perfect heat redistribution. We also estimate an orbit-averaged incident flux of $5.4 \times 10^7 \text{ erg s}^{-1} \text{ cm}^{-2}$, using the following formula:

$$\langle F \rangle = \sigma_B T_{\text{eff}}^4 \left(\frac{R_{\star}}{a} (1 - e^2/2) \right)^2, \quad (2)$$

and we find that TOI-4994b is below the B.-O. Demory & S. Seager (2011) insolation threshold of $2 \times 10^8 \text{ erg s}^{-1} \text{ cm}^{-2}$. Figure 9 highlights the mass and radius of TOI-4994b within the population of warm giant planets in the NASA Exoplanet Archive (R. L. Akeson et al. 2013). The planets are color coded by their reported equilibrium temperature.

The atmospheric composition of a planet provides key insights into its formation, history, and potential for habitability (see, e.g., N. Madhusudhan 2019). In order to assess the prospects for follow-up atmospheric characterization of TOI-4994b with JWST, we evaluated its transmission spectroscopy metric (TSM; E. M. R. Kempton et al. 2018). This value is proportional to the expected S/N of a transmission spectrum of the target, with higher numbers indicating better prospects for observation. We obtained a TSM value of 30 for TOI-4994b, which is below the value of 90 recommended by E. M. R. Kempton et al. (2018) for planets between 4 and $10 R_{\oplus}$.

Finally, we consider the feasibility of measuring the spin–orbit misalignment of the system via the RM effect or Doppler tomography. We estimate an expected RM signal of 8.3 m s^{-1} for TOI-4994b using Equation 12 of S. H. Albrecht et al. (2022), assuming a rotational velocity of $v \sin i_{\star} = 2.2 \text{ km s}^{-1}$, which is a typical value for G-type stars (e.g., L. A. dos Santos et al. 2016). Alternatively, using the predicted stellar rotation rate of 46.2 ± 3.1 days estimated in Section 3, we derived an RM signal of 4.3 m s^{-1} . Although TOI-4994 is slightly fainter than other stars hosting a warm giant, this signal is potentially observable with high-resolution instruments such as PFS, and we therefore encourage future follow-up observations to determine the system's spin–orbit alignment.

5. Conclusions

We presented the discovery and characterization of TOI-4994b, a warm Saturn transiting a moderately bright ($V = 12.6$ mag) G-type star in an eccentric 21.5 day orbit, discovered by

TESS. We confirmed the planetary nature of TOI-4994 with extensive ground-based photometry and with multiple high-resolution radial velocities from CHIRON, PFS, HARPS, FEROS, and CORALIE, and we ruled out the presence of nearby stellar companions with SOAR images. From our observations, we determined that TOI-4994 has physical properties similar to Saturn's and consistent with the population of known sub-Saturns. We encourage further observations of this system, as it is a promising candidate for spin–orbit angle measurements via the RM effect. Such observations could shed more light on the formation and evolution of these rare planets.

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Facilities: TESS, LCOGT, SOAR.

Software: AstroImageJ (K. A. Collins et al. 2017), EXOFASTv2 (J. D. Eastman et al. 2019), numpy (C. R. Harris et al. 2020), TAPIR (E. Jensen 2013).

Appendix RV Observations

In this section, we provide the corner plots from our analysis in Figure A1, and our radial velocity data in Table A1.

Table A1
RV Data

Time (BJD)	RV (m s ⁻¹)	RV error (m s ⁻¹)	Instrument
2460153.61049	4.40	4.13	PFS
2460153.62499	16.50	3.84	PFS
2460153.63926	16.49	3.43	PFS
2460154.60562	5.10	2.63	PFS
2460154.61980	8.69	2.45	PFS
2460154.63393	4.43	2.66	PFS
2460155.64044	5.92	2.36	PFS
2460155.65419	2.74	2.21	PFS
2460155.66844	14.53	2.18	PFS
2460156.65824	-8.11	2.47	PFS
2460156.67302	-7.01	2.44	PFS
2460156.68696	9.74	2.66	PFS
2460160.66059	-33.60	2.68	PFS
2460160.67464	-38.21	2.89	PFS
2460160.68876	-31.25	2.81	PFS
2460180.53256	-14.42	3.48	PFS
2460180.54735	2.14	3.30	PFS
2460180.56107	-16.94	3.67	PFS
2460184.54002	-40.53	4.71	PFS
2460210.52069	-7.26	3.66	PFS
2460210.53530	-5.42	3.68	PFS
2460210.54950	-8.28	3.58	PFS
2460212.51455	2.93	3.17	PFS
2460212.52869	0.00	2.76	PFS
2460212.54273	-5.89	2.62	PFS
2459819.56147	5965.0	32.0	CHIRON
2459822.57141	5992.0	28.0	CHIRON
2459825.47184	6030.0	28.0	CHIRON
2459828.63916	5984.0	31.0	CHIRON
2459838.46341	5994.0	26.0	CHIRON
2459841.54330	5984.0	31.0	CHIRON

Table A1
(Continued)

Time (BJD)	RV (m s ⁻¹)	RV error (m s ⁻¹)	Instrument
2459844.54869	6038.0	32.0	CHIRON
2459854.51278	6047.0	32.0	CHIRON
2459857.51441	6015.0	31.0	CHIRON
2459860.49822	5980.0	38.0	CHIRON
2459863.50449	5997.0	35.0	CHIRON
2459866.52502	6006.0	28.0	CHIRON
2459869.50415	6017.0	33.0	CHIRON
2459872.52953	6033.0	38.0	CHIRON
2459876.50716	6070.0	48.0	CHIRON
2459680.91764	5393.1	35.7	CORALIE
2459690.91570	5436.0	61.8	CORALIE
2459702.81753	5354.2	37.8	CORALIE
2459723.87356	5428.1	54.7	CORALIE
2459740.79469	5340.0	70.5	CORALIE
2459748.77041	5254.7	93.9	CORALIE
2459845.62784	5329.9	49.8	CORALIE
2459763.78280	5349.6	14.6	FEROS
2459764.78507	5330.3	11.4	FEROS
2459806.64321	5340.8	20.8	FEROS
2459808.62570	5358.8	10.1	FEROS
2459809.63296	5319.1	13.4	FEROS
2459810.67493	5291.7	12.0	FEROS
2459835.57461	5413.7	14.6	FEROS
2459847.63789	5393.9	17.4	FEROS
2459845.65994	5368.4	12.9	FEROS
2459851.60212	5363.3	14.1	FEROS
2459897.50622	5303.8	11.9	FEROS
2460032.88150	5288.0	10.3	FEROS
2460047.87740	5376.4	9.3	FEROS
2460066.86333	5401.1	9.8	FEROS
2460125.74290	5320.0	8.7	FEROS
2460149.76750	5331.6	9.9	FEROS
2460151.83118	5352.2	10.7	FEROS
2460178.52971	5335.2	12.1	FEROS
2460193.51918	5323.4	11.4	FEROS
2460194.69004	5445.8	16.0	FEROS
2460227.54377	5371.7	4.3	HARPS-1
2460239.52640	5402.2	4.8	HARPS-1
2460254.54061	5392.2	4.1	HARPS-1
2460262.53137	5391.3	3.7	HARPS-1
2460056.82106	5233.7	6.4	HARPS-2
2460058.85810	5242.8	8.2	HARPS-2
2460060.87608	5232.6	7.9	HARPS-2
2460062.90944	5237.2	7.4	HARPS-2
2460086.79806	5234.7	11.6	HARPS-2
2460089.81426	5250.6	6.3	HARPS-2

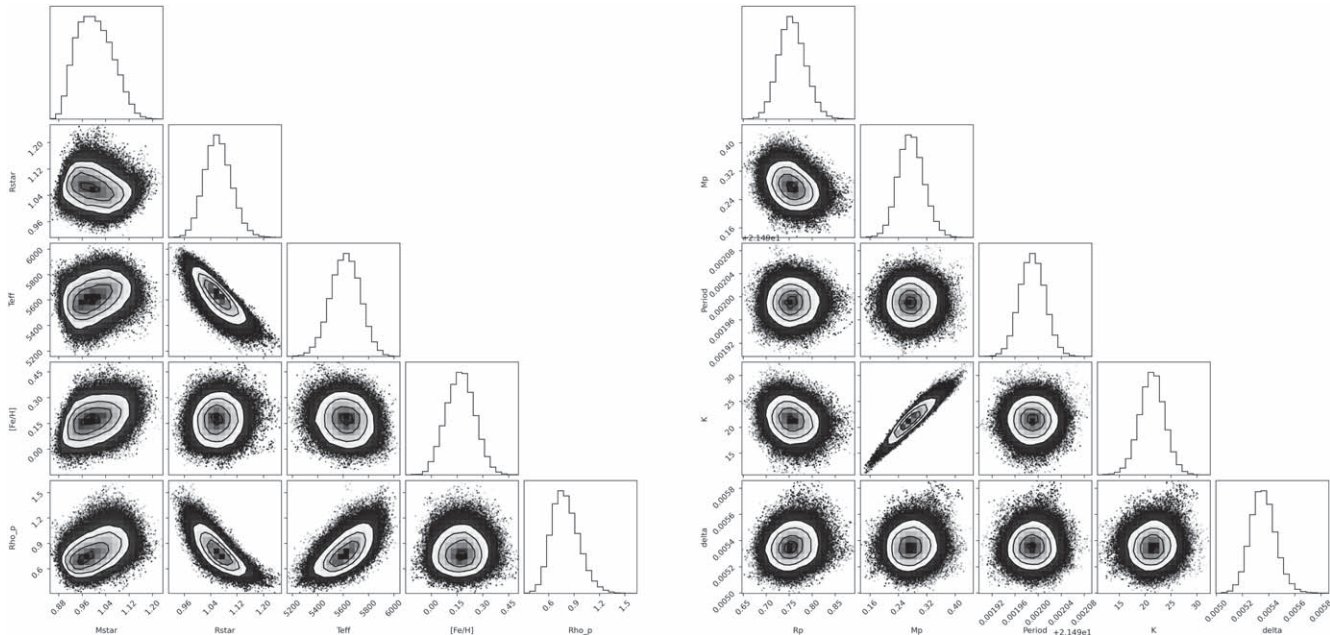


Figure A1. Corner plots showing the covariances for some of the stellar and planetary parameters in our analysis.

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References

- Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, *PASP*, **125**, 989
 Albrecht, S. H., Dawson, R. I., & Winn, J. N. 2022, *PASP*, **134**, 082001
 Bakos, G. Á., Csubry, Z., Penev, K., et al. 2013, *PASP*, **125**, 154
 Bakos, G. Á., Kovács, G., Torres, G., et al. 2007, *ApJ*, **670**, 826
 Barclay, T., Pepper, J., & Quintana, E. V. 2018, *ApJS*, **239**, 2
 Borucki, W. J., Koch, D., Basri, G., et al. 2010, *Sci*, **327**, 977
 Brady, M. T., Petigura, E. A., Knutson, H. A., et al. 2018, *AJ*, **156**, 147
 Brahm, R., Espinoza, N., Jordán, A., et al. 2019, *AJ*, **158**, 45
 Brahm, R., Jordán, A., & Espinoza, N. 2017, *PASP*, **129**, 034002
 Brahm, R., Nielsen, L. D., Wittenmyer, R. A., et al. 2020, *AJ*, **160**, 235
 Brahm, R., Ulmer-Moll, S., Hobson, M. J., et al. 2023, *AJ*, **165**, 227
 Brown, T. M., Baliber, N., Bianco, F. B., et al. 2013, *PASP*, **125**, 1031
 Butler, R. P., Marcy, G. W., Williams, E., et al. 1996, *PASP*, **108**, 500
 Caldwell, D. A., Tenenbaum, P., Twicken, J. D., et al. 2020, *RNAAS*, **4**, 201
 Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, *ApJL*, **529**, L45
 Collins, K. 2019, AAS Meeting Abstracts, 223, 140.05
 Collins, K. A., Kielkopf, J. F., Stassun, K. G., & Hessman, F. V. 2017, *AJ*, **153**, 77
 Crane, J. D., Shectman, S. A., & Butler, R. P. 2006, *Proc. SPIE*, **6269**, 626931
 Crane, J. D., Shectman, S. A., Butler, R. P., et al. 2010, *Proc. SPIE*, **7735**, 773553
 Crane, J. D., Shectman, S. A., Butler, R. P., Thompson, I. B., & Burley, G. S. 2008, *Proc. SPIE*, **7014**, 701479
 Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, *yCat*, **II/246**
 Daban, J.-B., Gouvet, C., Guillot, T., et al. 2010, *Proc. SPIE*, **7733**, 77334T
 Dawson, R. I., & Johnson, J. A. 2018, *ARA&A*, **56**, 175
 Demory, B.-O., & Seager, S. 2011, *ApJS*, **197**, 12
 dos Santos, L. A., Meléndez, J., do Nascimento, J.-D., et al. 2016, *A&A*, **592**, A156
 Dotter, A. 2016, *ApJS*, **222**, 8
 Dransfield, G., Triard, A. H. M. J., Guillot, T., et al. 2022, *MNRAS*, **515**, 1328
 Eastman, J. 2017, EXOFASTv2: Generalized Publication-quality Exoplanet Modeling Code, Astrophysics Source Code Library, ascl:1710.003
 Eastman, J., Gaudi, B. S., & Agol, E. 2013, *PASP*, **125**, 83
 Eastman, J. D., Rodríguez, J. E., Agol, E., et al. 2019, arXiv:1907.09480
 Eberhardt, J., Hobson, M. J., Henning, T., et al. 2023, *AJ*, **166**, 271
 Findeisen, K., Hillenbrand, L., & Soderblom, D. 2011, *AJ*, **142**, 23
 Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, *ApJ*, **659**, 1661

- Fortney, J. J., & Nettelmann, N. 2010, *SSRv*, **152**, 423
- Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, *A&A*, **674**, A1
- Gaudi, B. S., & Winn, J. N. 2007, *ApJ*, **655**, 550
- Gill, S., Wheatley, P. J., Cooke, B. F., et al. 2020, *ApJL*, **898**, L11
- Guillot, T., Abe, L., Agabi, A., et al. 2015, *AN*, **336**, 638
- Hansen, B. M. S., & Barman, T. 2007, *ApJ*, **671**, 861
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Natur*, **585**, 357
- Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, *ApJL*, **529**, L41
- Hobson, M. J., Brahm, R., Jordán, A., et al. 2021, *AJ*, **161**, 235
- Hobson, M. J., Trifonov, T., Henning, T., et al. 2023, *AJ*, **166**, 201
- Jenkins, J. M., Twicken, J. D., McCaulliff, S., et al. 2016, *Proc. SPIE*, **9913**, 99133E
- Jensen, E. 2013, Tapir: A Web Interface For Transit/eclipse Observability, Astrophysics Source Code Library, ascl:[1306.007](#)
- Johnson, M. C., Dai, F., Justesen, A. B., et al. 2018, *MNRAS*, **481**, 596
- Jordán, A., Brahm, R., Espinoza, N., et al. 2020, *AJ*, **159**, 145
- Kaufer, A., Stahl, O., Tubbesing, S., et al. 1999, *Msngr*, **95**, 8
- Kempton, E. M. R., Bean, J. L., Louie, D. R., et al. 2018, *PASP*, **130**, 114401
- Kley, W., & Nelson, R. P. 2012, *ARA&A*, **50**, 211
- Kurucz, R. L. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 225
- Lightkurve Collaboration, Cardoso, J. V. d. M., Hedges, C., et al. 2018, Lightkurve: Kepler and TESS Time Series Analysis in Python, Astrophysics Source Code Library, ascl:[1812.013](#)
- Lindgren, L., Klioner, S. A., Hernández, J., et al. 2021, *A&A*, **649**, A2
- Madhusudhan, N. 2019, *ARA&A*, **57**, 617
- Madhusudhan, N., Amin, M. A., & Kennedy, G. M. 2014, *ApJL*, **794**, L12
- Mamajek, E. E., & Hillenbrand, L. A. 2008, *ApJ*, **687**, 1264
- Mayor, M., Pepe, F., Queloz, D., et al. 2003, *Msngr*, **114**, 20
- McCully, C., Volgenau, N. H., Harbeck, D.-R., et al. 2018, *Proc. SPIE*, **10707**, 107070K
- Mékarnia, D., Guillot, T., Rivet, J. P., et al. 2016, *MNRAS*, **463**, 45
- Millholland, S. C., He, M. Y., & Zink, J. K. 2022, *AJ*, **164**, 72
- Müller, S., & Helled, R. 2023, *FrASS*, **10**, 1179000
- Nelson, R. P. 2018, in Handbook of Exoplanets, ed. H. J. Deeg & J. A. Belmonte, 139 (Berlin: Springer)
- Pecaut, M. J., & Mamajek, E. E. 2013, *ApJS*, **208**, 9
- Pepe, F., Mayor, M., Galland, F., et al. 2002, *A&A*, **388**, 632
- Pepper, J., Pogge, R. W., DePoy, D. L., et al. 2007, *PASP*, **119**, 923
- Petigura, E. A., Sinukoff, E., Lopez, E. D., et al. 2017, *AJ*, **153**, 142
- Pollacco, D. L., Skillen, I., Collier Cameron, A., et al. 2006, *PASP*, **118**, 1407
- Queloz, D., Mayor, M., Udry, S., et al. 2001, *Msngr*, **105**, 1
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *JATIS*, **1**, 014003
- Schlecker, M., Kossakowski, D., Brahm, R., et al. 2020, *AJ*, **160**, 275
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, **500**, 525
- Schmider, F.-X., Abe, L., Agabi, A., et al. 2022, *Proc. SPIE*, **12182**, 121822O
- Schulte, J., Rodríguez, J. E., Bieryla, A., et al. 2024, *AJ*, **168**, 32
- Smith, J. C., Stumpe, M. C., Van Cleve, J. E., et al. 2012, *PASP*, **124**, 1000
- Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, *AJ*, **158**, 138
- Stumpe, M. C., Smith, J. C., Catanzarite, J. H., et al. 2014, *PASP*, **126**, 100
- Stumpe, M. C., Smith, J. C., Van Cleve, J. E., et al. 2012, *PASP*, **124**, 985
- Thorngren, D. P., Fortney, J. J., Murray-Clay, R. A., & Lopez, E. D. 2016, *ApJ*, **831**, 64
- Tokovinin, A. 2018, *PASP*, **130**, 035002
- Tokovinin, A., Fischer, D. A., Bonati, M., et al. 2013, *PASP*, **125**, 1336
- Trifonov, T., Brahm, R., Espinoza, N., et al. 2021, *AJ*, **162**, 283
- Trifonov, T., Brahm, R., Jordán, A., et al. 2023, *AJ*, **165**, 179
- Udry, S., Mayor, M., Naef, D., et al. 2000, *A&A*, **356**, 590
- Van Eylen, V., Dai, F., Mathur, S., et al. 2018, *MNRAS*, **478**, 4866
- Vanderburg, A., & Johnson, J. A. 2014, *PASP*, **126**, 948
- Winn, J. N., & Fabrycky, D. C. 2015, *ARA&A*, **53**, 409
- Zacharias, N., Finch, C., & Frouard, J. 2017, *yCat*, **1340**
- Zhou, G., Rodríguez, J. E., Collins, K. A., et al. 2016, *AJ*, **152**, 136
- Ziegler, C., Tokovinin, A., Briceno, C., et al. 2019, arXiv:[1908.10871](#)