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TESS Giants Transiting Giants. VII. A Hot Saturn Orbiting an Oscillating Red **Giant Star***

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Abstract

We present the discovery of TOI-7041 b (TIC 201175570b), a hot Saturn transiting a red giant star with measurable stellar oscillations. We observe solar-like oscillations in TOI-7041 with a frequency of maximum power of $\nu_{\text{max}} = 218.50 \pm 2.23 \,\mu\text{Hz}$ and a large frequency separation of $\Delta \nu = 16.5282 \pm 0.0186 \,\mu\text{Hz}$. Our asteroseismic analysis indicates that TOI-7041 has a mass of $1.07\pm0.05(\text{stat})\pm0.02(\text{sys})$ M_{\odot} and a radius of 4.10 ± 0.06 (stat) ± 0.05 (sys) R_{\odot} , making it one of the largest stars around which a transiting planet has been discovered with the Transiting Exoplanet Survey Satellite (TESS), and the mission's first oscillating red giant with a transiting planet. TOI-7041 b has an orbital period of 9.691 ± 0.006 days and a low eccentricity of $e = 0.04 \pm 0.04$. We measure a planet radius of $1.02 \pm 0.03 R_{Jup}$ with TESS photometry, and a planet mass of $0.36\pm0.16 M_{Jup}$ (114±51 M_{\oplus}) with ground-based radial velocity measurements. TOI-7041 b appears less inflated than similar systems receiving equivalent incident flux, and its circular orbit indicates that it is not undergoing tidal heating due to circularization. The asteroseismic analysis of the host star provides some of the tightest constraints on the stellar properties of a TESS planet host and enables precise characterization of the hot Saturn. This system joins a small number of TESS-discovered exoplanets orbiting stars that exhibit clear stellar oscillations and indicates that extended TESS observations of evolved stars will similarly provide a path to improved exoplanet characterization.

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^{*} This paper includes data gathered with the 6.5 m Magellan Telescopes

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1. Introduction

Asteroseismology, the study of stellar oscillations, provides uniquely precise constraints on stellar properties. The power of asteroseismology for characterizing transiting planet hosts was made evident by the space-based observatories CoRoT (J. Ballot et al. 2011; Y. Lebreton & M. J. Goupil 2014) and Kepler (D. Huber et al. 2013; M. S. Lundkvist et al. 2016; V. Van Eylen et al. 2018). The K2 mission expanded the sample of oscillating planet hosts and provided key constraints on the properties of evolved stars and their planets (S. K. Grunblatt et al. 2019). By revealing precise stellar masses, radii, and ages, these missions enabled the best characterization of transiting exoplanets.

The Transiting Exoplanet Survey Satellite (TESS; G. R. Ricker et al. 2015) has dramatically expanded the sample of potential targets that can benefit from the synergy between asteroseismology and exoplanet science. According to prelaunch predictions, hundreds of solar-like oscillator planet hosts (primarily low-luminosity red giant branch stars) would be detected in TESS photometry (T. L. Campante et al. 2016). The discovery of TOI-197 b, a hot Saturn orbiting an oscillating subgiant, in the first year of the TESS mission indicated promising prospects for a growing sample (D. Huber et al. 2019). This was followed by the confirmation of TOI-257 b, a warm sub-Saturn orbiting an evolved F-type star (B. C. Addison et al. 2021). TESS has also been very successful at recovering stellar oscillation signals for stars previously known to host planets. Asteroseismology of known planet hosts has been used to precisely characterize numerous planets orbiting evolved stars (T. L. Campante et al. 2019; W. H. Ball et al. 2020; C. Jiang et al. 2020; M. B. Nielsen et al. 2020; J. Pepper et al. 2020; M. L. Hill et al. 2021; C. Jiang et al. 2023). D. Huber et al. (2022) showed the power of the 20 s cadence observations from TESS to study pulsations in solar analogs, using the well-studied π Men system as a test case. Beyond these early discoveries and measurements in known planet hosts, there has been a surprising lack of newly discovered oscillating planet hosts from TESS.

The amplitude of p-mode oscillations increases as a star evolves (W. J. Chaplin & A. Miglio 2013), making asteroseismic detections more likely for stars ascending the red giant branch. However, the increased radius and luminosity limit the likelihood of transit detection. The Giants Transiting Giants (GTG) survey (S. K. Grunblatt et al. 2022, 2023, 2024; N. Saunders et al. 2022, 2024; F. Pereira et al. 2024) uses a pipeline developed to identify planets transiting the most evolved stars, and therefore provides an ideal sample to search for oscillating hosts. The precise constraints that asteroseismology enables can be used to test a variety of longstanding questions in exoplanet science, such as whether hot Jupiters are reinflated at late times (S. K. Grunblatt et al. 2016, 2017; D. P. Thorngren et al. 2021) and how the occurrence rate of giant planets changes as a function of stellar evolutionary state (S. K. Grunblatt et al. 2019).

Here, we present a new planet discovery and confirmation from the GTG survey—TOI-7041 b, a hot Saturn orbiting an oscillating low-luminosity red giant. We detect p-mode oscillations in the TESS light curve of TOI-7041 and perform asteroseismic modeling to constrain the stellar properties.

2. Observations

2.1. TESS Photometry

We identified the transit signal of TOI-7041 b in the TESS Full Frame Image (FFI) light curve produced by the giants² pipeline (N. Saunders 2024). The transit was initially flagged in a visual search and submitted as a Community TESS Object Of Interest in 2021 May. TOI-7041 has been observed in the TESS FFIs in Sectors 1 and 2 at 30 minute cadence, 28 and 29 at 10 minute cadence, and 68 and 69 at 200 s cadence. This target additionally received 2 minute cadence observations during Sectors 68 and 69. The full TESS observational baseline spans ${\sim}1883$ days, from 2018 July 25 to 2023 September 20. The giants light curve used to identify TOI-7041 b was composed of data from the TESS FFIs for Sectors 1, 2, 28, and 29. We performed a box-least squares (BLS) search for periodic signals using the astropy.timeseries implementation of the BLS method (G. Kovács et al. 2002). Full details about our search pipeline can be found in N. Saunders et al. (2022). We confirmed that the transit signal is detected in the FFI light curves produced by the TESS-SPOC (D. A. Caldwell et al. 2020) and QLP pipelines (C. X. Huang et al. 2020), as well as the 2 minute cadence light curve produced by the SPOC pipeline (J. M. Jenkins et al. 2020). Moreover, the difference image centroiding test (J. D. Twicken et al. 2018) performed on the 2 minute data constrained the location of the transit source to within $11^{"}.9 \pm 6^{"}.8$ of the host star.

2.2. Radial Velocity Follow-up

We performed ground-based radial velocity (RV) follow-up with three instruments to measure the mass and orbital eccentricity of TOI-7041 b. We obtained five observations of TOI-7041 with the CHIRON optical echelle spectrometer (A. Tokovinin et al. 2013) on the SMARTS 1.5 m telescope at CTIO between 2023 June 30 and 2023 July 5. The median RV uncertainty of the CHIRON observations was 28.0 m s⁻¹.

We additionally obtained nine RV observations with the Carnegie Planet Finder Spectrograph (PFS; J. D. Crane et al. 2006, 2008, 2010) on the 6.5 m Magellan II telescope at Las Campanas Observatory in Chile. PFS is an optical echelle spectrograph with an iodine cell for wavelength calibration. Observations were obtained between 2024 May 26, and 2024 July 1. The median RV uncertainty of the PFS observations was 1.19ms^{-1} .

Finally, we observed TOI-7041 with the fiber-fed FEROS spectrograph mounted on the MPG 2.2 m (A. Kaufer et al. 1999) telescope at La Silla Observatory in Chile. These observations were performed in the context of the Warm Giants with TESS collaboration (R. Brahm et al. 2019, 2020; A. Jordán et al. 2020; M. J. Hobson et al. 2021; T. Trifonov et al. 2023). Twelve RVs were obtained between 2023 August 22 and 2024 August 19. FEROS spectra were obtained with the

²⁸ github.com/nksaunders/giants

simultaneous calibration mode and were processed with the automatic ceres (R. Brahm et al. 2017) pipeline. The FEROS observations have the longest single-instrument baseline in our data set, providing valuable information about the long-period RV variability. These data had a median RV uncertainty of 6.65 m s^{-1} . Table A1 in the Appendix contains the full list of all RV observations used in this work.

2.3. Ground-based Imaging

To rule out close stellar companions to TOI-7041, we obtained high-resolution imaging observations on 2024 September 18, with the Zorro optical speckle imager on the 8.1 m Gemini-South telescope, located in Cerro Pachón, Chile. We computed the detection limits in contrast (Δm) versus angular separation from the center of the stellar point-spread function in arcseconds to obtain the contrast curve, which is shown in Figure A1 in the Appendix. We calculated the contrast in both the 532 nm and 832 nm passbands. There are no significant spikes in the contrast curve above $\Delta m > 4$ in the 562 nm observation and $\Delta m > 5$ in the 832 nm observation, indicating that TOI-7041 has no close companions.

3. Host Star Characterization

3.1. High-resolution Spectroscopy

To measure atmospheric parameters we used an out-oftransit, iodine-free template PFS spectrum. We restricted our analysis to the wavelength range between 500 and 630 nm, for which the spectrum has a peak signal-to-noise ratio (SNR) of ~ 200 at ~ 580 nm. Continuum correction was performed by iteratively fitting fourth-order polynomials to the 90th percentile flux for each spectral order binned into 20 wavelength segments. The resulting continuum-normalized spectrum was then analyzed using iSpec (S. Blanco-Cuaresma et al. 2014) to derive atmospheric parameters. We used the turbospectrum synthesis code (B. Plez 2012) with MARCS model atmospheres (B. Gustafsson et al. 2008), solar abundances from N. Grevesse et al. (2007), and the Gaia ESO line list as implemented in iSpec (S. Blanco-Cuaresma et al. 2014), excluding the sodium doublet. We fitted for stellar effective temperature (T_{eff}) , surface gravity $(\log(g))$, metallicity ([M/H]), and projected stellar rotational velocity ($v \sin i$), with microturbulence and macroturbulence parameters fixed using the built-in iSpec relations. The resulting best-fit yielded $T_{\rm eff} = 4700$ K, $\log(g) = 3.2$ dex, and [M/H] = 0.25 dex, with no significant rotational broadening (<3kms⁻¹). The temperature is in good agreement with photometric estimates from isochrone fitting ($T_{\rm eff} = 4700$ K, Section 3.4) and the TESS Input Catalog ($T_{eff} = 4696$ K; K. G. Stassun et al. 2019). The surface gravity is furthermore in good agreement with asteroseismology (see Section 3.4). We adopt uncertainties of 100 K in $T_{\rm eff}$ (\approx 2%, following J. Tayar et al. 2022) and 0.1 dex in [M/H] (G. Torres et al. 2012; E. Furlan et al. 2018) to account for possible systematic errors between different methods.

3.2. Asteroseismic Detection

We performed a search for stellar p-mode oscillations in the TESS light curve of TOI-7041 to provide additional constraints on its stellar properties. First, we searched the TESS asteroseismic catalog produced by M. Hon et al. (2021) and



Figure 1. Amplitude spectrum of TOI-7041 centered on the range of frequencies showing stellar oscillations. The *y*-axis shows the SNR of the oscillation power at each frequency, calculated by dividing the power spectrum by the estimated background. The orange and blue lines show the identified $\ell = 0$ and $\ell = 2$ modes, respectively.

did not find reports of a seismic detection. Utilizing the TESS Asteroseismic Target List²⁹ (D. Hey et al. 2024) toolkit, we computed an asteroseismic detection probability for TOI-7041 of 100%. We then performed an independent search for stellar oscillations.

To produce our power spectrum we used the SPOCgenerated Presearch Data Conditioning Simple Aperture Photometry (PDCSAP; J. C. Smith et al. 2012; M. C. Stumpe et al. 2012; M. C. Stumpe et al. 2014) light curve composed of 2 minute cadence observations obtained in Sectors 68 and 69. PDCSAP light curves were selected as these data provided the highest SNR (additional discussion in Section 6.3). Using the lightkurve Python package (Lightkurve Collaboration et al. 2018), we calculated a Lomb-Scargle periodogram (N. R. Lomb 1976; J. D. Scargle 1982) of the TESS time series photometry to obtain the power at each frequency, ν . We estimate the background signal of the periodogram using a moving filter in $\log_{10} \nu$ space, and divide our power spectrum by the background to estimate the SNR. Using the resulting amplitude spectrum, we estimated the frequency of maximum power, $\nu_{\rm max}$, and large frequency separation, $\Delta \nu$. $\nu_{\rm max}$ was estimated by applying the 2D autocorrelation function (ACF) method (D. Huber et al. 2009; L. S. Viani et al. 2019) to the full amplitude spectrum, which identifies the global power excess. $\Delta \nu$ was estimated by analyzing the 2D ACF in a narrower region of the amplitude spectrum near ν_{max} . We assume the FWHM of the oscillation envelope is roughly given by FWHM $\approx 0.66\nu_{\text{max}}^{0.88}$ based on empirical relations (B. Mosser et al. 2010; M. N. Lund et al. 2017), and we compute the 2D ACF in a region of width $2 \times FWHM$ centered on the estimated $\nu_{\rm max}$. Using these methods, we identified a power excess with an envelope that peaks at a frequency of $\nu_{\rm max} \approx 220.5 \,\mu{\rm Hz}$ with a large frequency separation of $\Delta \nu \approx 16.45 \,\mu\text{Hz}$. Figure 1 shows the envelope of oscillations identified in the TESS light curve, centered on the frequency of maximum power.

We then performed seismic power spectrum modeling using the estimated values of ν_{max} and $\Delta\nu$ derived from the 2D autocorrelation as the initial values. We used the "peakbagging" code PBJam (M. B. Nielsen et al. 2021) to identify pairs of $\ell = 0$, 2 modes in the power spectrum with the PyMC3 (J. Salvatier et al. 2016) implementation of Hamiltonian Monte

²⁹ github.com/danhey/tess-atl



Figure 2. Frequency echelle diagram of the smoothed power spectrum. Orange points indicate the identified $\ell = 0$ modes and blue points indicate the $\ell = 2$ modes. Uncertainties on the identified mode frequencies are shown by the error bars; some uncertainties are smaller than the point size. The shading shows the SNR at each frequency.

Carlo sampling. We list the identified mode frequencies with their corresponding uncertainties in Table A2 in the Appendix. Using PBJam, we fit a Lorentzian profile to each mode and obtained the following constraints on the fundamental seismic parameters: $\nu_{max} = 218.50 \pm 2.23 \ \mu$ Hz and $\Delta \nu = 16.5282 \pm 0.0186 \ \mu$ Hz. We also constrain $\delta \nu_{02}$, the separation between the $\ell = 0$ and $\ell = 2 \ \text{modes}: \delta \nu_{02} = 2.0906 \pm 0.0491 \ \mu$ Hz. We adopt these values for our analysis of the stellar properties. Figure 2 shows the echelle diagram with modes identified by PBJam. The echelle diagram was produced by dividing the power spectrum into equal segments with length $\Delta \nu$ and stacking them vertically such that the $\ell = 0$ and $\ell = 2$ modes form ridges.

3.3. Luminosity Constraint

We used the isoclassify³⁰ Python package (D. Huber 2017; T. A. Berger et al. 2020) to compute the bolometric luminosity of TOI-7041. We ran the code in direct mode, providing observables from our spectroscopic fit (T_{eff} , [Fe/H]), the asteroseismic analysis (ν_{max} , $\Delta \nu$), Gaia Data Release 3 (DR3; position and parallax distance; Gaia Collaboration et al. 2023) as well as the *K*-band magnitude adopted from the Two Micron All-Sky Survey (2MASS; M. F. Skrutskie et al. 2006). We used the Combined19 all-sky dust map from mwdust (J. Bovy et al. 2016). From isoclassify, we report the luminosity, *L*, and distance, *d* in Table 1.

3.4. Stellar Modeling

We calculated the stellar mass (M_{\star}) , stellar radius (R_{\star}) , surface gravity $(\log(g))$, and age (τ) using a model grid created with the Modules for Experiments in Stellar Evolution (MESA;³¹ B. Paxton et al. 2010, 2013, 2015, 2018, 2019; A. S. Jermyn et al. 2023). We used the measured values of ν_{max} , $\Delta\nu$, T_{eff} , [M/H], and $\delta\nu_{02}$ (as reported in Table 1) to compute a likelihood function over the grid per the usual χ^2 discrepancy statistic, which we convert to posterior probabilities under uninformative uniform priors on the stellar age by dividing out the sampling function of the grid. We further impose an additional prior constraint excluding stellar ages above 13.8

 Table 1

 Stellar Properties Derived for TOI-7041

		TOI-7041	Source
TIC ID		201175570	(a)
R.A.		23:51:12.52	(a)
Decl.		-50:52:11.5	(a)
V magnitude		11.251 ± 0.026	(a)
K magnitude		8.691 ± 0.023	(a)
Gaia magnitude		10.9080 ± 0.0002	(a)
TESS magnitude		10.264 ± 0.006	(a)
$T_{\rm eff}$	(K)	4700 ± 100	(b)
[M/H]	(dex)	0.25 ± 0.10	(b)
$v \sin i_{\star}$	$({\rm km} {\rm s}^{-1})$	<3*	(b)
M_{\star}	(M_{\odot})	$1.07 \pm 0.05(\text{stat}) \pm 0.02(\text{sys})$	(c)
R_{\star}	(R_{\odot})	$4.10 \pm 0.06(\text{stat}) \pm 0.05(\text{sys})$	(c)
$\log(g)$	(dex)	$3.244 \pm 0.007(\text{stat}) \pm 0.001(\text{sys})$	(c)
au	(Gyr)	$10.3 \pm 1.9({\rm stat}) \pm 0.1({\rm sys})$	(c)
L	(L_{\odot})	$7.60^{+0.28}_{-0.26}$	(d)
d	(pc)	442 ± 3	(d)
$\nu_{\rm max}$	(μHz)	218.50 ± 2.23	(e)
$\Delta \nu$	(μHz)	16.5282 ± 0.0186	(e)
$\delta \nu_{02}$	(µHz)	2.0906 ± 0.0491	(e)

Note. Sources: (a) TESS input catalog v8.2 (K. G. Stassun et al. 2019); (b) spectroscopic fit (this work); (c) asteroseismic grid-based modeling (this work); (d) isoclassify (this work; D. Huber 2017; T. A. Berger et al. 2020); and (e) PBJam (this work; M. B. Nielsen et al. 2021). *Upper limit only.

Gyr using a half-Gaussian cutoff function at that age, with $\sigma = 0.5$ Gyr. We report the posterior-weighted mean, and take the posterior-weighted standard deviation across the grid to be a measure of our statistical uncertainty. We repeat this exercise using the model grid of C. J. Lindsay et al. (2024), which was constructed using different model physics, and take the absolute difference between the posterior means reported by the two grids as an estimate of the systematic modeling uncertainty. The resulting asteroseismic quantities and stellar properties are reported in Table 1. The stellar radius inferred from asteroseismology and the spectroscopic $T_{\rm eff}$ are shown in Figure 3.

We performed an independent analysis to infer the fundamental and photospheric stellar parameters of TOI-7041 using the isochrones (T. D. Morton 2015) package to execute with MultiNest (F. Feroz & M. P. Hobson 2008; F. Feroz et al. 2009, 2019) a simultaneous Bayesian fit of the MESA Isochrones and Stellar Tracks (MIST; J. Choi et al. 2016; A. Dotter 2016) isochrone grid to a curated collection of data for the star. We fit the MIST grid to the following photometric measurements: SkyMapper Southern Survey Data Release 4 uvgr photometry including in quadrature their zeropoint uncertainties (0.03, 0.02, 0.01, and 0.01, respectively) mag (C. A. Onken et al. 2024), Gaia Data Release 2 (DR2) G photometry including in quadrature its zero-point uncertainty (Gaia Collaboration et al. 2016, 2018; F. Arenou et al. 2018; G. Busso et al. 2018; D. W. Evans et al. 2018; M. Riello et al. 2018), 2MASS JHK_s photometry including their zero-point uncertainties (M. F. Skrutskie et al. 2006), and Wide-field Infrared Survey Explorer (WISE) CatWISE2020 W1W2 photometry including in quadrature their zero-point uncertainties (0.032 and 0.037, respectively) mag (E. L. Wright et al. 2010; A. Mainzer et al. 2011; P. R. M. Eisenhardt et al. 2020; F. Marocco et al. 2021). We also fit to the $\Delta \nu$ and ν_{max} reported in Table 1, a zero-point-corrected Gaia DR3 parallax

³⁰ https://github.com/danxhuber/isoclassify

³¹ Details about the construction of the grid used in this work can be found in the GitHub repository github.com/parallelpro/mesa-rc-mass-loss.



Figure 3. Stellar radius vs. stellar effective temperature for all confirmed transiting planet hosts. TESS discoveries are shown in black and discoveries from other telescopes are shown in gray. Systems discovered by the GTG survey are marked by orange circles, with TOI-7041 indicated by the filled orange point.

(Gaia Collaboration et al. 2021; C. Fabricius et al. 2021; L. Lindegren et al. 2021a, 2021b; N. Rowell et al. 2021; F. Torra et al. 2021), and an estimated extinction value based on a 3D extinction map (R. Lallement et al. 2022; J. L. Vergely et al. 2022).

As priors, we used a G. Chabrier (2003) lognormal mass prior for $M_* < 1 M_{\odot}$ joined to a E. E. Salpeter (1955) powerlaw prior for $M_* \ge 1 M_{\odot}$, a metallicity prior based on the Geneva–Copenhagen Survey (L. Casagrande et al. 2011), a log-uniform age prior between 1 and 10 Gyr, a uniform extinction (A_V) prior in the interval 0 mag $< A_V < 0.5$ mag, and a distance prior proportional to volume in the range of the C. A. L. Bailer-Jones et al. (2021) geometric distance $\pm 5 \times$ its uncertainty.

The isochrone fit provides an estimate of effective temperature $T_{\rm eff} = 4640 \pm 10$ K, surface gravity $\log(g) = 3.24 \pm 0.01$, metallicity $[{\rm Fe}/{\rm H}] = 0.39 \pm 0.02$, mass $M = 1.12 \pm 0.02$ M_{\odot} , radius $R = 4.20^{+0.03}_{-0.02}$ R_{\odot} , and age $\tau = 9.4 \pm 0.4$ Gyr. These constraints are broadly consistent with the stellar properties inferred by spectroscopy and asteroseismology. The joint posterior distributions for our fit parameters can be found in Figure A2 in the Appendix. We adopt the asteroseismic measurements of mass, radius, $\log(g)$, and age, and the spectroscopic constraints on $T_{\rm eff}$ and metallicity ([M/H]).

4. Planet Modeling

4.1. Simultaneous Transit and Radial Velocity Fitting

We used the exoplanet Python package (D. Foreman-Mackey et al. 2020) to simultaneously fit an orbital model to the photometry and RV observations. The data used in our model

 Table 2

 Best-fit Orbital Parameters for TOI-7041 b

		TOI-7041 b
Fitted parameters:		
Р	(days)	9.691 ± 0.006
t_0	(BJD)	2460160.393 ± 0.012
$R_{\rm p}/R_{\star}$		0.0256 ± 0.0006
a/R_{\star}		4.8 ± 0.1
b		0.2 ± 0.1
Κ	$(m \ s^{-1})$	36.2 ± 5.0
ω	(°)	131 ± 52
е		0.04 ± 0.04
Derived parameters:		
$M_{\rm p}$	$(M_{\rm Jup})$	0.36 ± 0.16
R _p	$(R_{\rm J}{\rm up})$	1.02 ± 0.03

fit were the PDCSAP TESS photometry for Sectors 68 and 69 and the 26 RV observations listed in Table A1. We parameterized the eccentricity by optimizing the parameters $\sqrt{e} \sin \omega$ and $\sqrt{e} \cos \omega$ where ω is the argument of periastron. This parameterization avoids biasing the model toward higher eccentricities during sampling (D. R. Anderson et al. 2011; J. Eastman et al. 2013). In our model, eccentricity e was bounded by $0 \le e < 1$ and the argument of periastron by $-\pi < \omega < \pi$. We use an eccentricity prior prescribed by the D. M. Kipping (2013) beta distribution. The other transit parameters we optimized were the ratio of planet radius (R_P) to stellar radius, R_P/R_* , impact parameter b, orbital period P, and midtransit time at the reference epoch t_0 . The RV components were parameterized with a separate RV offset and jitter term for each of the three instruments. To estimate mass, we optimized the semiamplitude *K* of the RV trend.

These distributions were created within a PyMC3 model (J. Salvatier et al. 2016), allowing us to optimize the model parameters using gradient descent. We sampled our model parameters using No U-Turn Sampling (M. D. Hoffman & A. Gelman 2014) with four chains of 4000 draws, with 4000 iterations used to tune the model.

We report our fit results in Table 2, adopting the median value of the posterior distribution for each parameter and its standard deviation as the uncertainty. Our resulting orbital models can be found in Figure 4, which shows the transit model fit (left) and the RV solution (right).

4.2. Search for Additional Planets

We searched for additional transiting planets in the TESS photometry by masking out the transits of TOI-7041 b and performing a BLS search on the resulting light curve. We searched a grid of 10,000 periods between 1 and 50 days and 1000 durations between 2 and 20 hr. No periodic signals were identified above an SNR of 10.

We also searched for signatures of nontransiting planets in the RVs. Using the RVSearch³² Python package, we calculated a Lomb-Scargle periodogram and searched the result for evidence of a single most-significant planet, then iteratively searched for additional periodic components in the RV time series. We identify an additional periodic signal at a period of 149.5 ± 0.1 days with an RV semiamplitude of $K = 55 \pm 6$ m s⁻¹. We searched the TESS light curve for

³² github.com/California-Planet-Search/rvsearch



Figure 4. (a) Phase-folded TESS light curve, centered on the transit of TOI-7041 b. Light gray points show the TESS observations, dark gray points show TESS data binned to 1 hr, and the orange line shows the best-fit transit model. (b) RV measurements obtained with CHIRON (light gray), FEROS (dark gray), and PFS (black), phase folded to the period of the transit signal. The orange line shows our best-fit orbital model, with random draws from the posterior distribution of the model shown by the fainter orange lines. The RV and transit models were fit simultaneously using the exoplanet Python package.

transits at times that would be consistent with this periodic RV component, and did not identify a transit in the single such time that occurred during a TESS observation.

Assuming the signal is planetary in origin and the orbit is observed near edge on, this amplitude would correspond to a planet mass of ~0.6 M_{Jup} . We perform our fitting routine with the inclusion of this trend, and the best-fit model reports a moderate eccentricity for the potential outer planet of $e = 0.23 \pm 0.07$. Our two-planet model is shown with the full RV time series in Figure 5. The additional signal has been removed from the phase-folded RV model for the transiting planet, TOI-7041 b, shown in Figure 4, right.

Due to the limited baseline of our observations relative to the measured period of the additional RV signal, further monitoring of this system is required to confirm that the variability is caused by a planetary companion. Stellar activity signals have been shown to produce false positive detections in RV observations, due to starspot modulation and magnetic or chromospheric variability (S. H. Saar & R. A. Donahue 1997; E. Delgado Mena et al. 2018; A. P. Hatzes et al. 2018; E. R. Simpson et al. 2022). These false positive cases can be identified through correlations between RV variability and flux variability in the photometric time series. However, we do not identify this long-period variability in the TESS light curve. Continued RV monitoring will reveal whether this signal is coherent over long timescales, which could rule out the false positive case.

5. Results

TOI-7041 b is a hot Saturn ($R_p = 1.02 \pm 0.03 R_{Jup}$, $M_p = 0.36 \pm 0.16 M_{Jup}$) on a 9.691 ± 0.006 day orbit around an oscillating red giant star. Our orbital model indicates that the planet's orbit is nearly circular ($e = 0.04 \pm 0.04$). By analyzing the asteroseismic signal observed in the TESS light curve of TOI-7041, we obtain estimates of the stellar mass $M_* = 1.07 \pm 0.05(\text{stat}) \pm 0.02(\text{sys}) M_{\odot}$, stellar radius $R_* = 4.10 \pm 0.06(\text{stat}) \pm 0.05(\text{sys}) R_{\odot}$, surface gravity $\log(g) = 3.244 \pm 0.007(\text{stat}) \pm =0.001(\text{sys})$ dex, and age $\tau = 10.3 \pm 1.9(\text{stat}) \pm 0.1(\text{sys})$ Gyr. TOI-7041 has an effective temperature of $T_{\text{eff}} = 4700 \pm 100$ K, which when considered along with its mass and radius indicates that the star is a red giant. When compared to MIST stellar models within 1σ of the



Figure 5. Full RV time series for TOI-7041 with our two-planet model shown in orange. In addition to the signal in phase with the transit ephemeris (shown as a phase-folded RV curve in Figure 4, right), we identify a periodic trend with a period of \sim 150 days.

observed $T_{\rm eff}$, M_{\star} , and R_{\star} , TOI-7041 is consistent with stars in the red giant phase.

6. Discussion

6.1. Comparison to Known Exoplanets

TOI-7041 may be the largest star with a confirmed planet discovered in TESS data. It is similar in both size and temperature (within 1σ of each) to TOI-2669 (GTG II; S. K. Grunblatt et al. 2022). The position of TOI-7041 on a Hertzsprung–Russell diagram can be found in Figure 3, where it may be compared to the population of TESS-discovered host stars. Hosts of confirmed planets from the GTG survey make up the majority of subgiant and red giant hosts from TESS. The confirmation of TOI-7041 b moves us closer to the largest planet hosts from Kepler—Kepler-91 (J. Lillo-Box et al. 2014) and Kepler-56 (J. H. Steffen et al. 2012)—and K2—K2-97 and K2-132 (S. K. Grunblatt et al. 2016, 2017; M. I. Jones et al. 2018). Figure 6 shows the orbital semimajor axis, *a*, as a function of stellar radius, R_{+} . Due to the large radius of its host,



Figure 6. Planetary orbital semimajor axis (*a*) shown as a function of stellar radius (R_{\star}) for all confirmed exoplanet (gray) and TOI-7041 b (orange). The solid black line shows the 1:1 relation where $a = R_{\star}$.



Figure 7. Planet radius vs. planet mass for all known exoplanets are shown in gray. The position of TOI-7041 b is marked by the orange point. Solar system planets Earth, Neptune, Saturn, and Jupiter are marked by their initials.

TOI-7041 b is positioned in the lower envelope of the distribution, near the line indicating the stellar surface ($a = R_{\star}$). This system is very near Kepler-56, K2-97, K2-132, and TOI-2669 in *a* versus R_{\star} space, while the closest point to the 1:1 line is Kepler-91.

Figure 7 shows the position of TOI-7041 b relative to all other confirmed exoplanets in radius versus mass. The planet's mass is close to that of Saturn (marked by the "S") and its radius is near 1 R_{Jup} .

6.2. Planet Radius Reinflation

The anomalously large radii of highly irradiated giant planets is a long-standing mystery in exoplanet science (B.-O. Demory & S. Seager 2011; G. Laughlin et al. 2011; N. Miller & J. J. Fortney 2011; J. D. Hartman et al. 2016), with important implications for our understanding of planet interior physics. Theoretical predictions have indicated that giant planets on short orbital periods should undergo rapid reinflation as their host stars brighten on the main sequence or as they become evolved (D. P. Thorngren et al. 2021). However, the TESS sample of hot



Figure 8. Planet radius shown as a function of incident flux the planet receives from its star. Point color indicates the planet mass. The dashed vertical line shows the inflation threshold from B.-O. Demory & S. Seager (2011). The estimated main-sequence incident flux received by TOI-7041 b is indicated by the white circle.

Jupiters orbiting evolved stars does not seem to follow as clear a radius-mass-flux relationship as the main-sequence population, instead displaying a wider range of radii at high incident fluxes (S. K. Grunblatt et al. 2022). Discoveries from TESS have also shown that lower-mass planets may be able to retain their atmospheres at higher incident fluxes than previously expected (S. K. Grunblatt et al. 2024).

We examined how the incident flux received by TOI-7041 b changed as its host star evolved. To estimate the incident flux received by the planet on the main sequence, we produced a stellar model with MESA. Using the stellar properties listed in Table 1, we initiated a stellar model and ran it from the premain sequence to the base of the red giant branch. We then identified the main-sequence effective temperature and radius and computed the incident flux. On the main sequence, TOI-7041 b likely received incident flux below the threshold for inflation of ~150 F_{\oplus} defined in B.-O. Demory & S. Seager (2011). At this level of incident flux, a radius of $\sim 1 R_{Jup}$ would not be inconsistent with the main-sequence population, though it places TOI-7041 b among the largest planets of similar mass. The measured radius of TOI-7041 b indicates that it may have undergone moderate reinflation as its host star evolved, but it is not significantly larger than systems which have not undergone a similar increase in incident flux.

Here, we compare TOI-7041 to two analog systems: K2-97 and K2-132. These systems are remarkably similar to TOI-7041, being composed of a low-luminosity red giant host star $(T_{\rm eff} \approx 4800 \text{ K}, R_{\star} \approx 4 R_{\odot})$ with a roughly Saturn-mass (~0.5 $M_{\rm Jup}$) planet orbiting with a period of ~9 days. We plot planet radius as a function of incident flux received from the host star in Figure 8. TOI-7041 b sits on the lower edge of the inflation trend, though its radius is consistent with other planets of similar mass, which span a wide range of radii in a similar range of incident flux (~10³ F_{\oplus}). When compared to the other evolved systems with similar planetary properties we have highlighted, TOI-7041 b is significantly smaller. Both K2-97 and K2-132 show substantial inflation, with radii near ~1.3 $R_{\rm Jup}$, compared to ~1 $R_{\rm Jup}$ for TOI-7041 b.

The incident flux received by TOI-7041 b is similar to that of K2-97 b and K2-132 b, and we must therefore consider additional heating mechanisms to explain the difference in

observed inflation. Tidal circularization of a planet's orbit can result in heat deposited deep in the planet's interior through tidal distortion (P. Bodenheimer et al. 2001). We measure a low eccentricity for TOI-7041 b ($e = 0.04 \pm 0.04$), indicating that the planet is not undergoing tidal heating due to circularization. Conversely, K2-97 b and K2-132 b show significant nonzero eccentricities of $e = 0.22 \pm 0.08$ and 0.36 ± 0.06 , respectively (S. K. Grunblatt et al. 2018). Given that eccentricity is the most-significant distinguishing factor between these two inflated systems and the less inflated planet reported in this work, it appears that heating due to tidal circularization may be a dominant source of late-stage planetary radius reinflation.

6.3. Prospects for Future Asteroseismic Detections

TOI-7041 was observed in six TESS sectors, which included 30 minute, 10 minute, and 2 minute cadence observations. The oscillation signature is clearly visible in the 2 minute cadence observations, weakly visible in the 10 minute cadence observations, and not detected in the 30 minute cadence observations. The peak frequency of the envelope of oscillations ($218.50 \pm 2.23 \mu$ Hz) is below the Nyquist limit for each of these cadences and should therefore be detectable, though the amplitudes are likely undergoing Nyquist attenuation at the longest cadence, which has a Nyquist limit of 283 μ Hz. The primary contributor to the difference in the recovered SNR of the oscillations between 10 and 2 minute cadence sectors is likely the light curve de-trending.

For the asteroseismic analysis reported in this work, we use only the 2 minute cadence PDCSAP light curve produced by the SPOC pipeline (J. M. Jenkins et al. 2016). We also performed the analysis using the combined amplitude spectra of the 30 minute, 10 minute, and 2 minute cadence light curves; however, we found that the inclusion of longer cadences resulted in an increasingly reduced SNR. Our longer-cadence light curves were produced using a variety of publicly available FFI pipelines, including TESS-SPOC (D. A. Caldwell et al. 2020), QLP (C. X. Huang et al. 2020), eleanor-lite (A. D. Feinstein et al. 2019), TGLC (T. Han & T. D. Brandt 2023), and our own giants pipeline. The recovery of oscillations with the highest SNR in the 2 minute cadence SPOC light curve indicates that the detrending applied by this pipeline preserves the oscillations and results in the lowest signal dilution from systematics or contaminating sources. D. Huber et al. (2022) showed that the details of how observations are processed and reduced are crucial to extracting the highest-quality oscillation signals at 20 s cadence, and similar effects may be true for other cadences. The signal should still be measurable in the longercadence FFI observations, and the retrieval of such asteroseismic signals may become possible as existing pipelines are adapted in the future. However, the results for TOI-7041 indicate that obtaining targeted short-cadence light curves which are processed by the SPOC pipeline may enable improved asteroseismic analysis.

A larger sample of asteroseismic measurements for evolved planet hosts would provide valuable information for investigations of key open questions related to the evolution of planetary systems. Improved radius precision will be particularly valuable to test planet radius inflation scenarios. Discoveries from the GTG survey have already provided valuable benchmarks, and precise measurements of the planets' properties from asteroseismology of their hosts are crucial to better test theoretical predictions for planetary atmosphere inflation and interior physics. The occurrence of giant planets as a function of stellar evolutionary state is also unclear. Some studies have suggested that giant planets should be depleted by tides before the star becomes a red giant (J. H. Hamer & K. C. Schlaufman 2019), while others have indicated that these planets survive to at least the base of the red giant branch and have a similar rate of occurrence to their main-sequence counterparts (S. K. Grunblatt et al. 2019). A large sample of evolved planet hosts with asteroseismic mass measurements would enable a direct comparison between similar stars at varied evolutionary states, providing a clearer look at the time dependence of planet occurrence.

7. Conclusions

Our main conclusions are as follows.

- 1. TOI-7041 b is a hot Saturn with a radius of $R_{\rm p} = 1.02 \pm 0.03 R_{\rm Jup}$ on a roughly circular orbit ($e = 0.04 \pm 0.04$) with an orbital period of $P = 9.691 \pm 0.006$ days.
- 2. RV observations show tentative evidence of an outer companion to TOI-7041 b with an orbital period of \sim 150 days. Further monitoring of this system is required to distinguish this trend from a stellar signal and constrain the orbit of the potential companion.
- 3. TOI-7041 b is significantly less inflated than similar systems (K2-97 b and K2-132 b), despite the similarities in the planet masses and incident fluxes. The low eccentricity measured for TOI-7041 b, when compared to the more eccentric orbits of K2-97 b and K2-132 b, indicates that the system is not undergoing tidal circularization, and points to tidal heating as a potential source of planet radius reinflation.
- 4. We measured solar-like oscillations in the TESS light curve of TOI-7041 that peak near $\nu_{\text{max}} = 218.50 \pm 2.23 \,\mu\text{Hz}$ and have a large frequency separation of $\Delta \nu = 16.5282 \pm 0.0186 \,\mu\text{Hz}$. This system joins a small number of TESS-discovered planets with asteroseismically characterized host stars, and is the first oscillating red giant host from TESS.
- 5. We performed grid-based asteroseismic modeling of the observed oscillation signal to infer precise stellar properties. TOI-7041 is one of the largest TESS stars known to host a transiting exoplanet, with a radius of $R_{\star} = 4.10 \pm 0.06(\text{stat}) \pm 0.05(\text{sys}) R_{\odot}$. We report an age for the system of $\tau = 10.3 \pm 1.9(\text{stat}) \pm 0.1(\text{sys})$ Gyr.
- 6. Stellar oscillations are observed with the highest SNR in the 2 minute cadence observations processed by the SPOC pipeline, indicating that we will likely recover additional asteroseismic detections as more targeted short-cadence observations of evolved stars are performed.

Despite a small number of asteroseismic planet hosts from TESS to date, the GTG survey has produced a large sample of promising targets for future asteroseismic analysis. The discovery and precise characterization of TOI-7041 b and similar systems will allow us to study in detail the changes that planetary systems undergo as their host stars evolve.

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Software: Lightkurve (Lightkurve Collaboration et al. 2018), Astropy (Astropy Collaboration et al. 2013; A. M. Price-Whelan et al. 2018; Astropy Collaboration et al. 2022), Astroquery (A. Ginsburg et al. 2019), PBJam (M. B. Nielsen et al. 2021), echelle (D. Hey & W. Ball 2020), exoplanet (D. Foreman-Mackey 2019; R. Luger et al. 2019), PyMC3 (J. Salvatier et al. 2016), giants (N. Saunders 2024), isochrones (T. D. Morton 2015), and R (R Core Team 2024).

Appendix Additional Figures and Tables

A.1. Radial Velocity Observations

Table A1 lists all RV observations used in this analysis.

Table A1				
Radial Velocity Observations Used in This Analysis				

Instrument	Time (BID)	RV	RV Error
monument	Time (DJD)	$(m s^{-1})$	$(m s^{-1})$
CHIRON	2460125.886770	-21	39
CHIRON	2460126.869260	20	28
CHIRON	2460128.846650	43	36
CHIRON	2460129.867900	46	27
CHIRON	2460130.884460	15	28
FEROS	2460178.691553	79.1	8.9
FEROS	2460179.764638	55.3	6.2
FEROS	2460268.663061	-59.8	6.9
FEROS	2460264.689207	45.8	6.1
FEROS	2460266.595236	5.3	6.1
FEROS	2460239.621033	-89.9	6.1
FEROS	2460310.538160	41.8	6.3
FEROS	2460317.564912	2.9	6.8
FEROS	2460513.811147	-45.3	8.0
FEROS	2460517.848128	-30.7	7.2
FEROS	2460534.788253	-27.6	6.5
FEROS	2460541.796333	-89.9	8.2
PFS	2460456.913340	65.02	1.62
PFS	2460456.922440	65.59	1.59
PFS	2460458.907970	68.67	1.16
PFS	2460462.916010	7.55	1.19
PFS	2460464.909460	37.50	1.09
PFS	2460485.896450	52.39	1.56
PFS	2460490.879490	8.16	1.13
PFS	2460491.843090	-3.79	1.19
PFS	2460492.832010	-8.07	1.15

Note. The instrumental offset for each observation has been subtracted from the reported RV value.

A.2. High-contrast Imaging

Figure A1 shows the contrast curve for TOI-7041 in two passbands—562 nm and 832 nm.



Figure A1. Contrast curve of TOI-7041 in the 562 nm and 832 nm passbands. The inset figure shows a high-contrast speckle image reconstruction centered on TOI-7041.

A.3. Asteroseismic Mode Identification

A.4. Isochrone Fitting Posteriors

Table A2 lists the pulsation modes identified by PBJam with their frequencies and uncertainties.

In Figure A2, we show the joint posterior distributions for the stellar properties fit with our isochrone grid. A detailed description of the analysis can be found in Section 3.4.

Order ℓ	Frequency	Uncertainty
	(μHz)	(μHz)
0	138.81	0.48
0	155.17	0.51
0	171.62	0.47
0	187.91	0.57
0	204.61	0.07
0	221.02	0.04
0	237.91	0.47
0	254.08	0.56
0	270.83	0.50
2	136.72	0.48
2	153.09	0.51
2	169.54	0.50
2	185.86	0.33
2	202.44	0.51
2	218.74	0.38
2	235.46	0.11
2	252.23	0.52
2	268.71	0.47

 Table A2

 Frequencies of Identified Pulsation Modes and Their Uncertainties



Figure A2. Joint posterior distributions from our isochrone grid modeling of TOI-7041.

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