TOI-2076 and TOI-1807: Two Young, Comoving Planetary Systems within 50 pc Identified by TESS that are Ideal Candidates for Further Follow Up

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Abstract

We report the discovery of two planetary systems around comoving stars: TOI-2076 (TIC 72491137) and TOI-1807 (TIC 180695581). TOI-2076 is a nearby (41.9 pc) multiplanetary system orbiting a young (204 ± 50 Myr) star, bright (K = 7.115 in TIC v8.1) start. TOI-1807 hosts a single transiting planet and is similarly nearby (42.58 pc), similarly young (180 ± 40 Myr), and bright. Both targets exhibit significant, periodic variability due to starspots, characteristic of their young ages. Using photometric data collected by TESS we identify three transiting planets around TOI-2076 with radii of Rp = 3.3 ± 0.04 R⊕, Rp = 4.4 ± 0.05 R⊕, and Rp = 4.1 ± 0.07 R⊕. Planet TOI-2076b has a period of Pb = 10.356 days. For both TOI-2076c and d, TESS observed only two transits, separated...
1. Introduction

A primary aim of exoplanetary science is to use the observed properties of planetary systems to constrain theoretical models of planet formation (which occurs in the protoplanetary disk) and evolution (which occurs after disk dispersal). This problem is approached in a number of ways: by forward modeling of the formation and evolution processes and comparison between simulated and observed exoplanet populations (“planet population synthesis”); e.g., Mordasini et al. 2009); through measuring the dependence of planet occurrence rates on fundamental stellar properties such as mass (e.g., Howard et al. 2012; Yang et al. 2020), metallicity (e.g., Fischer & Valenti 2005; Petigura et al. 2018), or multiplicity (e.g., Wang et al. 2014a, 2014b); and via case studies of individual systems that challenge conventional wisdom about the planet formation process (e.g., Carter et al. 2012; Lopez & Fortney 2013).

Young exoplanets (<1 Gyr) are particularly useful for case studies, as they have had less time to evolve and may therefore have properties that more closely resemble their initial conditions. In older planetary systems, disentangling the effects of planet formation from those of subsequent evolution becomes a more challenging task. However, of the more than 3300 transiting exoplanets con

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Unified Astronomy Thesaurus concepts: Exoplanets (498); Transits (1711); Time series analysis (1916)

by a 2 yr interval in which no data were collected, preventing a unique period determination. A range of long periods (<17 days) are consistent with the data. We identify a short-period planet around TOI-1807 with a radius of $R_p = 1.8 \pm 0.04 R_{\oplus}$ and a period of $P_p = 0.549$ days. Their close proximity, and bright, cool host stars, and young ages make these planets excellent candidates for follow up. TOI-1807b is one of the best-known small ($R < 2 R_{\oplus}$) planets for characterization via eclipse spectroscopy and phase curves with JWST. TOI-1807b is the youngest ultra-short-period planet discovered to date, providing valuable constraints on formation timescales of short-period planets. Given the rarity of young planets, particularly in multiple-planet systems, these planets present an unprecedented opportunity to study and compare exoplanet formation, and young planet atmospheres, at a crucial transition age for formation theory.

NASA Exoplanet Archive (Akeson et al. 2013), accessed in 2021 March. continues to evolve over billions of years (Berger et al. 2020; Sandoval et al. 2021) and that the precise location of the radius gap evolves on similar timescales (David et al. 2021). These results are broadly consistent with expectations from the photoevaporation and core-powered mass-loss models. However, the age of any individual field star typically carries large uncertainties.

The TESS mission (Ricker et al. 2015) provides a new opportunity for targeted searches of young exoplanets from precise time-series photometry for millions of targets across most of the sky. For example, the THYME survey has identified several planets in known young associations spanning a diversity of Galactic environments, such as the Tucana-Horologium and Ursa Major moving groups (Newton et al. 2019; Mann et al. 2020), the Scorpius-Centaurus OB association (Rizzuto et al. 2020), the Piscis-Eridanus stream (Newton et al. 2021), and even a previously unknown association (Tofflemire et al. 2021). Other searches of TESS data have revealed planets orbiting young stars in the IC 2602 cluster (Bourna et al. 2020) and in the field (Zhou et al. 2021).

Here we present the discovery of two young planetary systems: first, a system of three exoplanets orbiting a bright ($K = 7.715$), K-type variable star TOI-2076 (TIC 27491137), and second, a single short-period exoplanet orbiting its similarly bright comoving companion TOI-1807 (TIC 180695581). Stellar parameters for these targets are given in Tables 1 and 2, and planet parameters derived for each planet are given in Tables 4 and 5. We derive ages of $204 \pm 50$ Myr and $180 \pm 40$ Myr for TOI-2076 and TOI-1807, respectively. With its bright magnitude and close proximity of 41.91 \, pc in Gaia DR2 (Gaia Collaboration et al. 2018), TOI-2076 presents a rare opportunity to characterize a range of small-radius planets orbiting a young, active star. Owing to their young ages, both TOI-2076 and TOI-1807 are excellent candidates for studying the atmospheres of close-in planets existing around the transition age where photoevaporation is theorized to cease. Among short-period, small planets, TOI-1807 is one of the most amenable to phase-curve and eclipse spectroscopy.

Section 2 of this paper discusses the TESS observations of TOI-2076 and TOI-1807. Section 3 discusses our corrections to the TESS light curves to obtain more precise photometry and the model fit of the stellar SEDs and planet transits. Sections 4 and 5 discuss the statistical validation of all planets in these two systems and ground-based follow up. In Section 6 we discuss our age estimates for both targets. We conclude in Section 7 with a discussion of the importance of TOI-2076 and TOI-1807 to the community and demonstrate that each of these planets is an excellent candidate for further atmospheric follow up.
Other Identifiers

| Parameter | Description | Value | Value | Source |
|-----------|-------------|-------|-------|--------|
| α2000    | R.A.        | 13:25:07.9959 | 14:29:34.2428 | 1 |
| δ2000    | decl.       | +38:55:20.9460 | +39:47:25.5450 | 1 |
| G        | Gaia G mag. | 9.68 ± 0.02 | 8.91 ± 0.02 | 1 |
| BP       | Gaia BP mag. | 10.26 ± 0.02 | 9.37 ± 0.02 | 1 |
| RP       | Gaia RP mag. | 8.99 ± 0.02 | 8.33 ± 0.02 | 1 |
| T        | TESS mag.   | 9.036 ± 0.006 | 8.375 ± 0.006 | 2 |
| J        | 2MASS J mag. | 8.103 ± 0.023 | 7.613 ± 0.020 | 3 |
| H        | 2MASS H mag. | 7.605 ± 0.020 | 7.188 ± 0.027 | 3 |
| KS       | 2MASS KS mag. | ... | 7.115 ± 0.020 | 3 |
| WISE1    | WISE1 mag.  | 7.395 ± 0.03 | 7.01 ± 0.05 | 4, 5 |
| WISE2    | WISE2 mag.  | 7.508 ± 0.03 | 7.13 ± 0.03 | 4, 5 |
| WISE3    | WISE3 mag.  | 7.445 ± 0.051 | 7.09 ± 0.03 | 4, 5 |
| WISE4    | WISE4 mag.  | 7.368 ± 0.115 | 7.0 ± 0.1 | 4, 5 |
| μ      | Gaia DR2 proper motion in R.A. (mas yr⁻¹) | −124.713 ± 0.027 | −118.228 ± 0.036 | 1 |
| μ      | Gaia DR2 proper motion in decl. (mas yr⁻¹) | −27.377 ± 0.039 | −6.973 ± 0.048 | 1 |
| π        | Gaia Parallax (mas) | 23.4877 ± 0.042 | 23.8622 ± 0.0384 | 1 |

Notes. The uncertainties of the photometry have a systematic error floor applied.

Table 2

| Parameter | Units | Value | Value |
|-----------|-------|-------|-------|
| Stellar Parameters: | | TOI-2076 | TOI-1807 |
| $M_*$ | Mass ($M_\odot$) | 0.850$^{+0.025}_{-0.026}$ | 0.750$^{+0.025}_{-0.024}$ |
| $R_*$ | Radius ($R_\odot$) | 0.761 ± 0.016 | 0.680 ± 0.015 |
| $L_*$ | Luminosity ($L_\odot$) | 0.3777$^{+0.0041}_{-0.0092}$ | 0.2135 ± 0.0053 |
| $F_{bol}$ | Bolometric flux (cgs) | 6.88 ± 0.17 | 3.769 ± 0.092 |
| $\rho_*$ | Density (cgs) | 2.72$^{+0.17}_{-0.16}$ | 3.36$^{+0.23}_{-0.21}$ |
| log(g) | Surface gravity (cgs) | 4.605$^{+0.018}_{-0.019}$ | 4.648$^{+0.023}_{-0.029}$ |
| $T_{eff}$ | Effective temperature (K) | 5187$^{+74}_{-53}$ | 4757$^{+53}_{-78}$ |
| [Fe/H] | Metallicity (dex) | −0.032$^{+0.048}_{-0.047}$ | −0.029$^{+0.061}_{-0.043}$ |
| [Fe/H]0 | Initial metallicitya | −0.069 ± 0.054 | −0.065$^{+0.062}_{-0.053}$ |
| Age | Age (Gyr) | 0.204$^{+0.053}_{-0.050}$ | 0.180$^{+0.044}_{-0.038}$ |
| EEP | Equal evolutionary phaseb | 241.3$^{+7.5}_{-7.5}$ | 228.8$^{+6.6}_{-7.5}$ |
| $A_V$ | V-band extinction (mag) | 0.0139$^{+0.0039}_{-0.0092}$ | 0.017$^{+0.010}_{-0.011}$ |
| $\sigma_{SED}$ | SED photometry error scaling | 1.03$^{+0.42}_{-0.25}$ | 1.76$^{+0.68}_{-0.41}$ |
| $\pi$ | Parallax (mas) | 23.863$^{+0.049}_{-0.039}$ | 23.487 ± 0.042 |
| $d$ | Distance (pc) | 41.906 ± 0.069 | 42.577 ± 0.076 |

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

Table 1

| Parameter | Description | Value | Value | Source |
|-----------|-------------|-------|-------|--------|
| TOI-1807 | TIC 180695581 | HIP 65469 | TYC 3025-00731-1 |
| TOI-2076 | TIC 27491137 | ... | TYC 3036-00481-1 |

2. Observations

2.1. TESS Photometry

TOI-2076 was observed twice by TESS, once by camera 4 during Sector 16 (2019 September 11–October 7) and then again by camera 2 during Sector 23 (2019 March 18–2020 April 16). TOI-1807 was observed in Sector 22 (2020 February 19–March 17) and Sector 23. Both targets were observed in two-minute cadence mode. The literature properties of both targets are shown in Table 1.

2.1.1. By-eye Search

TOI-2076 was first identified by a student-led, by-eye search. Our by-eye search method was as follows; we downloaded two-minute cadence TESS Target Pixel Files (TPFs) for Sector 16 that had been calibrated by the TESS Science Processing Operations Center (SPOC) pipeline and summed pixels within the pipeline-provided aperture to create Simple Aperture Photometry (SAP) light curves. Outliers were then rejected using a standard deviation of 10σ. Stellar variability was subtracted using the flatten tool from the Python package lightcurve,44 which applied a Savitsky Galay filter over a 1001 cadence window to remove long-term trends on timescales of 1.5 days. The resulting light curve was plotted and visually inspected. Over 500 targets were processed before TOI-2076 was identified as an interesting candidate using Sector 16 data on 2020 March 8.

The TESS Pipeline-processed image data for TOI-2076 was accessed by our team in 2020 February. The pipeline-processed Pre Data-search Conditioned Simple Aperture Photometry

44 https://github.com/keplerGO/lightcurve
(PDCSAP) photometry available at that time for TOI-2076 suffered from spurious, semiperiodic signals with durations on the order of 0.59 days, which is at timescales and amplitudes comparable to the planet transits. This ultimately adversely affected the planet transit search and planet-modeling efforts (see Figure 1). By performing a by-eye search of the SAP flux generated from the TPFs, with no systematics corrections applied, our team was able to identify three, high signal-to-noise transiting objects in the Sector 16 data. We use the techniques described in Section 3 to detrend the SAP flux derived from the TESS products and improve precision before fitting the transits in the data. We later identified TOI-1807 as a comoving target also in the TOI list (see Section 2.2). Our processed light curves for TOI-2076 and TOI-1807 are shown in Figure 2, alongside the PDCSAP flux that was originally obtained. Figure 2 shows that, particularly in the case of TOI-2076, there is an increase in spurious noise, which hampered pipeline detection efforts. Since we accessed the data, the TESS pipeline data have been reprocessed, and the newly available PDCSAP light curves show greatly improved the correction. We include the original PDCSAP light curves for illustration in Figure 1, compared to the pipeline-provided SAP flux.

### 2.2. Comoving Targets

TOI-2076 and TOI-1807 were identified as a comoving pair of stars by Oh et al. (2017) because, after accounting for geometric projection, their proper motions are consistent with having the same three-dimensional velocity. Using updated astrometry and radial velocity (RV) data from Gaia EDR3, the stars have a mean heliocentric distance of 42.3 pc, a physical separation of 9.2 pc, and an angular separation of ~12.5 arcsec. While the stars have a proper motion difference of ~21.5 mas yr⁻¹, this is largely due to their large angular separation: the 3D velocity difference between the stars is only ~0.6 km s⁻¹ (5th and 95th percentile of 0.39 and 1.58 km s⁻¹, respectively). Even though recent Gaia data confirm that these stars are comoving, their large physical separation suggests that these objects are not a bound wide binary but could instead be part of a small moving group. The shared formation history (indicated by their three-dimensional velocity and similar ages) and similar stellar parameters of TOI-2076 and TOI-1807 make them a further interesting laboratory for testing planet formation theory.

### 3. Data Analysis

After identifying TOI-2076 as a planet host by eye and TOI-1807 as a comoving planet host among the public TOI list, we perform the following analysis to extract the planet parameters. In this analysis we use the lightkurve Python package to create SAP light curves of TOI-2076 from the TESS SPOC pipeline (Jenkins et al. 2016) TPFs. Sky background light from Earth is a significant systematic in TESS, which the pipeline corrects in TPF products. In this work, we use TPFs without background subtraction, because the SPOC pipeline masks cadences where the background is estimated to be severe, leading to data loss. Instead, we perform a bespoke background correction that includes these cadences, in order to preserve the most time-series data. This correction is discussed in Section 3.1.

#### 3.1. Light-curve Creation

We create light curves for TOI-2076 and TOI-1807 using the following procedure. The results of this procedure are shown in Figure 3.

1. Using our basic, mean-normalized SAP flux light curves from Section 2.1, we estimate periods, transit midpoints, and durations for each transiting planet.
2. We use the TESS Pipeline TPF products for TOI-2076 in Sectors 16 and 23, and for TOI-1807 from Sectors 22 and 23, conservatively removing cadences where the quality flags are consistent with “Coarse Point,” “Desaturation,”
or “Argabrightening” (flags 4, 32, and 16), which cause significant outliers. TPFs are delivered with a background light estimate subtracted by the pipeline. We use the FLUX_BKG keyword in the TPF FITS files to add the TESS Pipeline background correction back into the TPF (resulting in uncorrected, but calibrated TPFs). As discussed above, this enables us to perform a bespoke background correction and preserve more data that the pipeline flags as poor quality close to the data downlink.

3. We build light curves from the TPFs using the pipeline-provided apertures. Because these stars are isolated and the TESS pipeline estimates that more than 99.9% of the light in the apertures comes from the target stars (based on the pipeline’s crowding metric), contamination from background sources is negligible, and we do not apply a dilution correction.

4. We detrend these light curves to remove the background signal, using lightkurve’s RegressionCorrector tool. We model the light curve as a linear combination of (1) the top three components of the pixels outside the aperture using singular value decomposition (SVD), (2) a vector containing (i) the mean and (ii) the standard deviation of each of the three quaternions (available in the TESS engineering data; see Vanderburg et al. 2019) during each individual TESS exposure to account for TESS jitter, and (3) a basis spline with 80 evenly spaced knots between the start and end of the sector to capture the stellar variability. We fit this model, using Gaussian priors, masking out cadences that we expect to contain transiting planet signals.

This procedure results in light curves with long-term stellar variability removed, while transits remain intact in the data set. Using the estimate_cdpp method from lightkurve we estimate the photometric precision of all the light curves to determine the improvement in precision we obtain. The official TESS pipeline computes the Combined Differential Photometric Precision (CDPP) metric using a wavelet-based algorithm to calculate the signal-to-noise ratio of the specific waveform of transits of various durations (see Christiansen et al. 2012). In the lightkurve implementation, we use the simpler “sgCDPP proxy algorithm” discussed by Gilliland et al. (2011) and Van Cleve et al. (2016). Using this estimate the PDCSAP light curves available in 2020 for TOI-2076 and TOI-1807 have an sgCDPP of 100 and 164, respectively, for a 1 hr transit duration in parts per million (PPM). The procedure we describe here reduces the sgCDPP to 82 and 86 PPM, respectively, which indicates a significant reduction in noise. Having improved the precision of the light curves, we re-searched both TOI-2076 and TOI-1807 light curves to search for any shallower transiting signals using a simple Box Least Squares (BLS), but find no evidence of additional planets.

We use lightkurve and astropy to perform a basic Box Least Squares (BLS) search for transiting signals in the light curves of both targets. We identify three transiting objects around TOI-2076 with periods of 10.35 days, 17.19 days, and 25.08 days, and transit depths of 913 ± 19 ppm, 1906 ± 28 ppm, and 1181 ± 32 ppm. TOI-2076b transits four times during Sector 16 and Sector 23, TOI-2076c and TOI-2076d transit once in each in Sector 16, and once each in Sector 23. We identify a single transiting object around TOI-1807 during Sector 22 and Sector 23. Using a simple
BLS, TOI-1807b has a period of 0.55 days and a transit depth of $271 \pm 11$.

### 3.2. Spectroscopic Stellar Parameters

In order to refine the stellar parameters upon which the planetary parameters depend, we fit the stellar spectra and stellar spectral energy distributions (SEDs) for TOI-2076 and TOI-1807.

We obtained two reconnaissance spectra of TOI-2076 on UT 2020 February 20 and UT 2020 February 24, using the 1.5 m Tillinghast Reflector Echelle Spectrograph (TRES; Furesz 2008) located at the Fred Lawrence Whipple Observatory (FLWO) in Arizona, USA. For TOI-1807, we obtained...
two spectra on UT 2020-05-31 and UT 2020 July 1 with the Fibre-fed Echelle Spectrograph (FIES; Telting et al. 2014) at the 2.56 m Nordic Optical Telescope (NOT) in La Palma, Spain, and another spectrum with TRES on UT 2020 July 19. TRES has a resolving power of $R \approx 44,000$ with wavelength coverage from 3860 to 9100 Å, while FIES offers a resolution of $R \sim 67,000$ and covers the range 3760–8220 Å.

All of the spectra are extracted as described in Buchhave et al. (2010). We derive stellar parameters using the Stellar Parameter Classification tool (SPC; Buchhave et al. 2012, 2014). SPC compares an observed spectrum against a grid of synthetic spectra based on Kurucz atmospheric models (Kurucz 1992). We analyze each spectrum independently to obtain the effective temperature ($T_{\text{eff}}$, surface gravity ($\log g$)), metallicity ([M/H]), a solar mix of metals rather than Fe alone, and projected rotational velocity ($v \sin i$). The individually derived parameters agree to within their respective uncertainties, and we report their weighted average: TOI-2076 has $T_{\text{eff}} = 5227 \pm 50$ K, $\log g = 4.56 \pm 0.10$, [M/H] = −0.15 ± 0.08. TOI-1807 has $T_{\text{eff}} = 4830 \pm 50$ K, $\log g = 4.65 \pm 0.10$, [M/H] = −0.09 ± 0.08, and $v \sin i = 4.3 \pm 0.5$ km s$^{-1}$. These values are derived from spectra alone. These estimates are used to inform our SED fit in Section 3.3.

### 3.3. Spectral Energy Distribution

To determine the properties of both host stars, we perform a spectral energy distribution fit of the broadband photometry from Gaia DR2 (Gaia Collaboration et al. 2018), 2MASS (Cutri et al. 2003), and WISE (Cutri et al. 2012; Zacharias et al. 2017) using the publicly available exoplanet-fitting suite, EXOFASTv2 (Eastman et al. 2013, 2019). This SED fit also used the MESA Isochrones and Stellar Tracks stellar evolution models (Choi et al. 2016; Dotter 2016) to constrain the host-star parameters. We place a Gaussian prior on the Gaia DR2 parallax of 23.862 ± 0.0384 mas for TOI-2076 and 23.488 ± 0.042 mas for TOI-1807, which have been corrected for the known offset as described in Gaia Collaboration et al. (2018). We also place Gaussian priors on the metallicities determined by analyzing the TRES spectra (see Section 3.2) and host-star ages (0.188 ± 0.053 Gyr for TOI-2076 and 0.17 ± 0.04 Gyr for TOI-1807; see Section 6.1). Using the galactic dust maps from Schlegel et al. (1998) and Schlafly & Finkbeiner (2011), we place upper limits on the line-of-sight extinction of 0.02635 mag (TOI-2076) and 0.0313 mag (TOI-1807). The resulting best-fit parameters and the 68% confidence intervals are shown in Table 2.

### 3.4. Planet Model Fit

We use the exoplanet package\(^ {45}\) (Foreman-Mackey et al. 2020) and pycm3 (Salvatier et al. 2016) to fit the transit signals, given the best-fit stellar parameters derived above, using the light curves from our correction procedure described in Section 3.1. exoplanet is a probabilistic model, which allows us to create distributions for each parameter and jointly model them. Using exoplanet we are able to sample each parameter using Markov Chain Monte Carlo (MCMC), including any derived parameters (e.g., the semimajor axis is derived from the period and the stellar properties). In the case of TOI-2076, we jointly fit a single set of stellar parameters (i.e., stellar density and limb darkening) and three transiting planets.

To fit the transiting planets in the data set, we first remove stellar variability. We use the spline term from our fit to detrend the stellar variability by dividing the light curve by the best-fit spline component from Section 3. Because the stellar variability is long period, we assume that the stellar variability can be adequately detrended and does not require a joint fit with planet parameters. In the case of TOI-1807, we tested a joint fit for stellar variability and transits and found no significant improvement. For TOI-1807, we fit a single-planet model, and for TOI-2076 we fit a model consisting of three planets, in circular orbits, simultaneously. We assume that eccentricity cannot be measured using these data, as there are relatively few transits of each planet. (We explore eccentricities and period aliases of planets c and d in Section 3.6.) We fit for the period, transit midpoint, planet radius, impact parameter, and limb darkening in our model, and set the starting stellar parameters to those derived above, with Gaussian priors. We find the maximum likelihood fit and then use an MCMC No-U-Turn Sampler to find errors on each variable. The priors of our model are given in Table 3, and results of this fit are shown in Tables 4 and 5 and Figure 4, which shows good agreement with the data. We marginalize over the errors in the stellar parameters from Section 3.3.

### 3.5. Phase-curve Modeling

TOI-2076b is a short-period, hot planet with an equilibrium temperature of $>2000$ K. Given the high signal-to-noise light curve of the bright host star, it may be possible to use the TESS data to identify a phase curve; a simple calculation of

\(^{45}\) https://docs.exoplanet.codes/en/stable/
the maximum surface brightness ratio of TOI-2076b gives an eclipse depth of \( \sim 20 \) ppm. We additionally fit a transit model for TOI-1807 with an eclipse and phase-curve component, jointly fitting stellar variability. Using this approach, we are unable to detect a significant phase curve using the TESS data.

We additionally undertook the following search for a phase curve in the TESS Pipeline Products. First, the transits of TOI-1807 and the expected occultation events were removed from the observed TESS light curve. The photometry was separated into segments defined by each TESS orbit, then normalized by their average flux offset and detrended using a linear function that best-fit each light-curve segment. (We note that detrending each segment by a higher degree polynomial did not significantly alter our results.) Significant stellar variability was removed from the light curve by subtracting the two strongest sinusoidal signals detected in a Lomb–Scargle periodogram of the out-of-transit light curve at 4.34 days and 6.06 days. Finally, the variability corrected out-of-transit light curve was fit with a double harmonic sinusoidal model to search for an atmospheric phase-curve signature at the orbital period of TOI-1807b. The double harmonic sinusoidal model is defined as

\[
F(\phi) = A_n + A_r \cos 2\pi \phi + A_b \sin 2\pi \phi + A_e \cos 4\phi, \tag{1}
\]

where \( A_n \) is the flux normalization offset and \( A_r, A_b, \) and \( A_e \) represent the effects of planetary emission/reflection, Doppler boosting, and ellipsoidal variations, respectively. To determine the significance of the best-fit phase-curve model, the reduced \( \chi^2 \) statistic was compared to that of a horizontal line.

Regardless of whether we used (1) the TESS Pipeline SAP photometry, (2) PDCSAP photometry, (3) a correction for stellar variability, or (4) a higher-order polynomial (up to 10th degree) to detrend the light curve, we did not detect a significant atmospheric phase curve for TOI-1807b. In all cases, the best-fit phase-curve model was either consistent with a horizontal line or exhibited a \(<3\sigma\) significance phase-curve shape that is inconsistent with the expected shape of a planetary atmospheric phase curve.

We conclude that using the TESS data alone, there is no detectable phase curve for TOI-1807b. However, TESS data from future cycles may increase the signal to noise, or additional data at redder wavelengths may reveal a phase curve for this planet. TOI-1807 will be observed again by TESS in Sector 49, in 2022 February.

### 3.6. Period Aliases of TOI-2076c and TOI-2076d

We find best-fit periods for TOI-2076c and TOI-2076d of 17.19343 \( \pm 0.00037 \) days and 25.08872 \( \pm 0.00029 \) days respectively. Our best-fit periods reflect the shortest period, in each case, that is consistent with the data. However, due to the long gap between TESS observations, many aliased periods are also fit well by the data.
a “simple” orbit, where each planet occults the star, not on a circular orbit, but traveling on a straight path. This occultation is parameterized by the velocity of the planet. By adopting this approach, none of the parameters are forced by our prior knowledge of Keplerian laws (which link, for example, duration and impact parameter), and each parameter (e.g., impact parameter) is only constrained by the data itself. We set up this model such that each planet passes in front of the same star, with the same radius and limb-darkening parameters, and use MCMC (e.g., see Section 3.4) to vary all parameters in our model.

We perform a Monte Carlo analysis combining the posteriors from the simple transit fit with inferences based on both (1) dynamical stability and (2) the window function of allowed orbital periods derived from the observation times of the TESS sectors. This method of constraining orbital periods follows the line of analysis in Vanderburg et al. (2016) and Becker et al. (2019). For each link of the transit fit posterior, we take parameters for each planet and then numerically solve the following equation for \( P \), the planetary orbital period (see Seager & Mallén-Ornelas 2003):

\[
D = \frac{P}{\pi} \arcsin \left( \frac{\left[ \frac{G(M_\star + m_p)P^2}{4\pi^2} \right]^{-1/3}}{\sqrt{(r_P + R_\star)^2 - (b^2 \times R_\star^2)}} \right) \left[ \frac{\sqrt{1 - e^2}}{1 + e \cos \omega} \right].
\]

The parameters taken from the observationally derived posterior include \( D \), which is the transit duration of the planet; \( r_p \), which is the planetary radius; \( m_p \), which is the planetary mass; \( e \), which is the orbital eccentricity; \( \omega \), which is the longitude of periastron; \( b \), which is the planet’s impact parameter; and \( R_\star \) and \( M_\star \), which are the stellar radius and mass. Additional parameters that cannot be directly derived from the light curve must be computed: the planet mass \( m_p \) is inferred using the mass–radius relation of Wolfgang et al. (2016), \( e \) was chosen using a beta distribution prior with shape parameters \( \alpha = 0.867 \) and \( \beta = 3.03 \) (Kipping 2013b, 2014; Kipping & Sandford 2016), and then \( \omega \) was chosen using Equation (19) of Kipping & Sandford (2016). Finally, \( G \) is defined as the gravitational constant. For each link of the posterior, we solve Equation (2) numerically for each planet to derive the orbital period that corresponds to the observed parameters.

Once a set of two orbital periods (one for TOI-2076c and one for TOI-2076d) has been computed from a single link, we check two markers of dynamical instability: whether the chosen initial parameters are Hill unstable (Fabrycky et al. 2014) and whether the computed secular oscillation amplitudes in eccentricity (computed using the Laplace–Lagrange secular disturbing function; see Murray & Dermott 1999) result in orbits that cross. If either of those conditions is met, the link is thrown out; if not, the computed periods are kept and used to construct a probability density function for orbital periods that are consistent with the data and also likely dynamically stable. We then combine that with the baseline prior (see Equation (1) of Becker et al. 2019 and the general form in Equation (2) of Dholakia et al. 2020) to construct a final probability density function for each possible orbital period. The baseline prior also corrects this final probability to zero for any orbital period where a third transit should have been observed anywhere in the TESS data.

Using this final probability density function for each planet’s orbital period, we check each possible orbital period (corresponding
to a positive integer number of conjunctions in between the two observed transits.

and normalize the probabilities using those discrete values as the only possible orbital periods. For TOI-2076d, the most likely orbital period is 25.089 days (with a 60% probability), which corresponds to a circular orbit. The next most likely orbital period is 29.271 days, followed by 35.125 days and 43.906 days. For TOI-2076c, a secure determination of the best candidate period cannot be made. Orbital periods that have a greater than 10% chance of being correct given the above analysis include (in order of computed likelihood) 23.641 days, 21.014 days, 27.018 days, 18.913 days, and 17.193 days. Of these, 18.913 days and 17.193 days had the greatest positive correlation in occurrence with the 25.089 day orbital period for TOI-2076d. The 17.193 day orbital period for TOI-2076c also corresponds to a circular orbit.

To characterize the full state of the system, it is important to confirm the true orbital periods and subsequently refine the ephemerides and limits on transit timing variations. The determination of TOI-2076d’s orbital period is likely to be more straightforward, given the strong preference for the 25.089 day solution. TOI-2076c will be harder to constrain. We discuss ground-based data of TOI-2076 in the context of TOI-2076c in Section 5.

4. Vetting and Validation

In this section we discuss the validation of the planet candidates around TOI-2076 and TOI-1807. In Section 4.1 we discuss the constraints on contamination by background objects, using archival data, and show that archival data are able to rule out contamination for TOI-1807. In Section 4.2 we show there are no significant centroid offsets during transit, indicating that TOI-2076 and TOI-1807 are both the true sources of the planet signal. In Section 5.2, we use the TRICERATOPS toolkit (Giacalone et al. 2021) to show that there is a very small false probability chance in either the case of TOI-2076 or TOI-1807.

We additionally note that Gaia DR2 provides the Renormalized Unit Weight Error (RUWE; Lindegren 2018) to determine whether Gaia astrometric fits are good. A value significantly above 1 indicates that a single source is not a good fit to the data. TOI-2076 has a RUWE of 1.0857, and TOI-1807 has a RUWE of 1.07523, suggesting that they are consistent with being single stars.

4.1. Contamination (Archival Data)

Figure 5 shows the potential contamination of TOI-2076 and TOI-1807 using archival data. We downloaded images from the first and second Palomar Observatory Sky Survey (Minkowski & Abell 1963; Reid et al. 1991), as well as PanSTARRS (Chambers et al. 2016), and plotted the present-day position of the stars from the TIC (Stassun et al. 2018; propagating the proper motion forward to the time of TESS observations). We overplot the apertures assigned by the SPOC Pipeline that we use to extract the TESS light curves. Owing to the high proper motion of TOI-2076 and TOI-1807, the POSS I Blue image shows a significant offset between the centroid of the targets and their present-day positions.

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to rule out the presence of a contaminating source for TOI-2076 fainter than 11th mag using archival data alone.

We note that in POSS II and PanSTARRS there are some fainter targets contained within the SPOC pipeline aperture at the edge, and so we additionally perform a centroid test.

4.2. Contamination (Centroiding)

We perform a simple centroid test on the TESS data of TOI-2076 and TOI-1807 using the following procedure.

1. We estimate the centroid of the pixels within the SPOC Pipeline aperture using a weighted mean (weighted by the flux in each pixel). We propagate uncertainties by sampling from the flux errors for each pixel given by the pipeline.

2. We correct these centroids for long-term trends by removing a smooth trend built by a Gaussian smoothing kernel, with a default width of 21 cadences, using astropy’s convolution module. This removes long-term trends due to velocity aberration and focus change during a single TESS observation.

3. We then compare the X and Y centroid position distribution of cadences with no transits to cadences containing transits of planets. Using a simple Student t-test, we test whether the means of these distributions are consistent, assuming they have the same variance. We use scipy.stats.ttest_ind function to perform this test.

The tool to produce this centroid test is available as an open-source project on GitHub and available as a pip installable tool named vetting. The results of our centroid test are shown in Figure 6. We find for all planets, in all sectors, that there is no significant offset in the means of the centroid distributions. We find no significant evidence that there is any change in the target centroid during transits; our Student t-test has a p-value of $\geq 0.8$ for each transit, in each sector. This shows there is a $\geq 80\%$ probability that the distributions have the same mean, (i.e., that the centroids during transit are consistent with centroids out of transit.) We calculate the 1σ errors in separation from our centroid test for each planet in each sector. The distance at which we can rule out blends at the 1σ level is given in the corner of each panel of Figure 6. For TOI-2076 we can rule out blends to distances of 7″, 4″, and 6″ at the 1σ level for TOI-2076b, TOI-2076c, and TOI-2076d, respectively. For TOI-1807 we can rule out blends to distances of 10″ at the 1σ level for TOI-1807b. As such, we find no evidence that the transits originate from background sources, based on the TESS data alone. Further validation with external data sources is discussed below.

4.3. High-resolution Imaging Follow Up

We observed TOI-2076 and TOI-1807 on UT 2020 December 2 using the ShARCS camera on the Shane 3 m telescope at Lick Observatory (see Figure 7, top row). Observations were taken using the Shane adaptive optics (AO) system in natural guide star mode. We collected our observations using a four-point dither pattern with a separation of 4″ between each dither position. For TOI-2076, we obtained one sequence of observations in the Br-$g$ band with exposure times of 15 s, which rule out companions with $\Delta \text{mag} > 3$ at 0.5″ and companions with $\Delta \text{mag} > 4.5$ at 1″. For TOI-1807, we obtained one sequence of observations in the $K$ band with exposure times of 1.5 s, which rule out companions with $\Delta \text{mag} > 3$ at 0.5″ and companions with $\Delta \text{mag} > 4$ at 1″. See Savel et al. (2021) for a detailed description of the observing strategy and reduction procedure.

We obtained speckle interferometric images of TOI-2076 (see Figure 7, bottom row) on UT 7 February 2021 using the ‘Alopeke instrument mounted on the 8 m Gemini North telescope on the summit of Maunakea in Hawai‘i. We also obtained speckle interferometric images of TOI-1807 on UT 2020 June 9. ‘Alopeke simultaneously collects diffraction-limited images at 562 and 832 nm. Our data set consisted of 4 minutes of total integration time taken as sets of 1000 x 0.06 s images followed by the observation of a local PSF standard star. As discussed in Howell et al. (2011), we combined all images, subjected them to Fourier analysis, and produced reconstructed images from which the 5σ contrast curves are derived in each passband. The bottom row in Figure 7 presents the two contrast curves as well as the 832 nm reconstructed image for TOI-2076 and TOI-1807. Our measurements reveal TOI-2076 and TOI-1807 have no nearby, contaminating stars. For TOI-2076, we are confident of our determination of no companions to contrast limits of 5–8 mag, within the spatial limits of 0.7 au (562 nm) to 1.18 au (832 nm) at the inner working angle out to 50 au at 1″ (d = 42 pc). For TOI-1807, we are confident in our determination of no companions of $\Delta \text{mag} < 3$ at 0.5″ (21 au) and companions of $\Delta \text{mag} < 4$ at 1″ (42 au).

5. Ground-based Photometry

We acquired ground-based time-series follow-up photometry of TOI-1807b and TOI-2076c as part of the TESS Follow-up Observing Program (TFOP). We used the TESS Transit Finder, which is a customized version of the Tapir software package (Jensen 2013), to schedule our transit observations. The photometric data were extracted using AstroImageJ (Collins et al. 2017).

We observed a full transit window of TOI-1807b, as predicted by the SPOC pipeline analysis of TESS sector 22, on UTC 2020 April 19 in the Sloan i′ band from the 0.5 m CDK20N telescope at the University of Louisville Moore Observatory near Louisville, Kentucky. We observed a second full transit window on UT 2020 April 25 in the PanSTARRS z-short band from the Las Cumbres Observatory Global Telescope (LCOGT; Brown et al. 2013) 1.0 m network node at McDonald Observatory. Because the ~378 PPM event detected by the SPOC pipeline is generally too shallow to detect with ground-based observations, we checked for a faint nearby eclipsing binary (NEB) that could be contaminating the SPOC photometric aperture. To account for possible contamination from the wings of neighboring star PSFs, we searched for NEBs at the positions of Gaia DR2 stars out to 2.5 from the target star. If fully blended in the SPOC aperture, a neighboring star that is fainter than the target star by 8.6 mag in the TESS band could produce the SPOC-reported flux deficit at midtransit (assuming a 100% eclipse). To account for possible delta-magnitude differences between the TESS band and Sloan i′ band and PanSTARRS z-short band, we included an extra 0.5

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46 github.com/ssdatalab/vetting
47 https://pypi.org/project/vetting/
48 https://www.gemini.edu/instrumentation/alopeke-zorro
49 https://tess.mit.edu/followup
magnitudes fainter (down to TESS-band magnitude 17.7). We visually compared the light curves of the 4 nearby stars that meet our search criteria with models that indicate the timing and depth needed to produce the $\sim 400$ ppm event in the SPOC photometric aperture. We found no evidence of an NEB that might be responsible for the SPOC detection. By a process of elimination, we conclude that the transit is likely occurring in TOI-1807, or a star so close to TOI-1807 that it was not...
detected by Gaia DR2 and too faint to be detected by high-resolution imaging.

We observed a predicted egress of TOI-2076c on UTC 2020 December 29 in PanSTARRS $z$-short band from the LCOGT 1.0 m node at McDonald Observatory. The observation would contain a transit egress of TOI-2076c if the period were the shortest period estimate derived in Section 3.6 ($^{+17.1936}_{-17.19342}$ days). The TOI-2076c observation was moderately defocused, resulting in a typical point source FWHM of $\sim7''$, and used 15 s exposures. A photometric aperture radius of $\sim12''$ was used to extract the differential photometry, resulting in $\sim870$ ppm model residuals in 5 minute bins. The photometric aperture is not contaminated with flux from any known Gaia DR2 neighboring stars. We recover a a $\sim2000$ ppm egress using LCO data alone. The follow-up light-curve data are available at ExoFOP-TESS.\footnote{https://exofop.ipac.caltech.edu/tess}

We jointly fit the TESS data for TOI-2076c with the ground-based LCO data, fitting every period that is consistent with the data derived in Section 3.6. We simultaneously detrend the LCO data against the reported air mass for the observation, and fit for a variable mean offset. We calculate the reduced chi-squared fit of the model to the data and find a slight preference for the period of 17.1936 days. Figure 8 shows the best-fitting model with the LCO data for TOI-2076c. Given that we were able to obtain a single egress event, we find moderate evidence that the period of 17.1936 days is the correct period for TOI-2076c. If this is the correct period for TOI-2076c, this would put TOI-2076c and TOI-2076b very close to an orbital resonance of 5:3. Further data is needed to well constrain the period of TOI-2076c.

5.1. MuSCAT2 Observations

MuSCAT2 (Narita et al. 2019) is a multicolor optical camera mounted on the 1.52 m Telescopio Carlos Sánchez (TCS) at
flux contamination from nearby stars, the assumption that the transit originates from within the resolution limits of the target star is not valid for many planet candidates, so tools like vespa (Morton 2015; which was originally designed to validate planet candidates from Kepler and later adapted to TESS) are less widely applicable. vespa operates assuming that the transit originates from within the resolution limits of the target star, and therefore cannot be used for many TESS planet candidates. However, because the photometric follow up described in Section 4.3 rules out nearby resolved stars as transit sources for both TOI-1807 and TOI-2076, both of these tools can be used to validate planet candidates in these systems.

As an additional constraint in our calculations, we fold in the high-resolution imaging follow-up observations discussed in Section 4.3. Because these observations reveal no previously unresolved companions within their detection limits, incorporating the follow up reduces the calculated probability of the transit originating from a boundary or chance-aligned star within the resolution limits of the target star, thereby reducing the overall false-positive probability (FPP) for each target. The ground-based follow up presented above directly informs our statistical validation. Below, we present the results of this analysis for each planet candidate.

5.2.1. TOI-2076

We run triceratops for the three planet candidates around TOI-2076 20 times each and calculate the mean and standard deviation of the resulting distributions of FPPs. We find $\text{FPP} = (2.2 \pm 9.6) \times 10^{-6}$, $\text{FPP} = (2.2 \pm 9.7) \times 10^{-15}$, and $\text{FPP} = (1.2 \pm 5.1) \times 10^{-9}$ for planets b, c, and d, respectively. We also run vespa a single time for each planet candidate and find $\text{FPP} = 4.6 \times 10^{-3}$, $\text{FPP} = 3.8 \times 10^{-3}$, and $\text{FPP} = 6.6 \times 10^{-10}$, respectively. These probabilities are low enough to consider the three planets validated.

5.2.2. TOI-1807

We run triceratops for the planet candidate around TOI-1807 20 times and calculate the mean and standard deviation of the resulting distribution of FPPs. We find $\text{FPP} = (6.7 \pm 9.5) \times 10^{-6}$, which is below the threshold of FPP = 0.015 required to validate a planet candidate with this tool. We run vespa a single time to ensure that the two tools provide the same result. With vespa, we find $\text{FPP} = 1.4 \times 10^{-13}$. With these results strongly suggesting that the planet candidate is a bona fide planet, we consider the planet to be validated.

6. Estimating the Age of TOI-1807 and TOI-2076

We make use of a number of indicators to estimate the ages of TOI-2076 and TOI-1807. Young stars retain much of the angular momentum from their formation. As a result of the rapid rotation, young stars also exhibit extensive spot coverage and chromospheric activity. As such, for young Sun-like stars, we can often estimate their ages by their rotation periods, as measured from the light curve, and from the chromospheric activity indicators, such as core emission in the Ca II lines, and their UV and X-ray fluxes. We describe each of these indicators in the sections below.

Figure 9 presents a summary of the quantitative age estimates we provide. We adopt the 3σ gyrochronology age estimates of 130–210 Myr for TOI-1807 and 125–230 Myr for TOI-2076 in our analyses. We show below that each of the

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Figure 8. TOI-2076c observations from TESS, folded at 17.1936 days, with ground-based LCO data binned using a median to a cadence of 8 minutes. We perform a joint fit of the transit model and the instrument systematics for the ground-based data, jointly detrending against the measured air mass of the LCO observation. When comparing our fit for all periods quoted in Section 3.6, we find modest evidence that a period of 17.1936 provides the best fit to the data. Given the multiple periods that are equally likely from Section 3.6, we suggest it may be close to an orbital resonance with TOI-2076b, but further data are needed for a firm detection.

Figure 9 presents a summary of the quantitative age estimates we provide. We adopt the 3σ gyrochronology age estimates of 130–210 Myr for TOI-1807 and 125–230 Myr for TOI-2076 in our analyses. We show below that each of the
other activity and spectroscopic indicators support these gyrochronology estimates. We caution, however, that estimating the ages of single stars is always rife with caveats, and the estimates we provide should be taken with the necessary caution as is appropriate for their uncertainties.

6.1. Gyrochronology

Sun-like stars with convective envelopes and radiative cores spin down over their main-sequence lifetimes as mass is lost in the form of stellar wind. By comparing the rotation periods of our target stars against members of clusters and moving groups with known ages, we can place constraints on their ages. TOI-1807 and TOI-2076 exhibit significant spot-induced rotational modulation in their light curves. We make use of the TESS continuous light curves and archival ground-based multiyear observations to estimate the rotation periods of these stars.

TOI-2076 received two sectors of TESS observations over \(\sim28\) day segments in 2019 September and 2020 March, with significant spot evolution between the two separate sets of observations. We find a rotation period of \(6.84 \pm 0.58\) days and \(7.22 \pm 0.77\) days during Sectors 16 and 23, respectively (see Figure 10). The uncertainties are estimated based on the FWHM of the Lomb–Scargle periodogram peaks for each sector of observations. In addition, we made use of 8 yr of light curves from KELT (Pepper et al. 2007, 2012, 2018), spanning between 2006 and 2014 December. A Lomb–Scargle periodogram showed a peak at 7.31 days, consistent with that measured from the TESS observations. Taking the mean and the scatter in the measured periods between TESS and KELT, we get a rotation period for TOI-2076 of \(7.27 \pm 0.23\) days.

TOI-1807 received two sectors of continuous TESS observations over a period of 54 days, showing consistent stellar variability at the 2% level. The Lomb–Scargle periodograms for each sector of the TESS observations are shown in Figure 10. Our initial analysis yielded a highest peak in the periodogram of \(4.32 \pm 0.25\) and \(4.317 \pm 0.26\) days for Sectors 22 and 23, respectively. However, further analysis of the long-duration monitoring from the ground-based KELT survey showed that the TESS period peak is actually one-half that of the true rotation period. TOI-1807 was observed by the KELT survey from 2006 to 2014 December. The periodogram derived from these observations is also shown in Figure 10, with a best-matching period of 8.737 days, \(2\times\) that from the TESS light curves. Given the extensive coverage from the KELT survey and the rapid evolution expected for such young stars, we adopt a period of \(8.670 \pm 0.048\) days for TOI-1807.
6.2. Stellar Activity

As a result of the rapid rotation, young stars exhibit significant chromospheric emission visible in the X-ray and specific activity-sensitive optical features.

TOI-1807 and TOI-2076 are X-ray sources in the ROSAT All-sky survey (Voges et al. 2000). We convert the X-ray fluxes to X-ray luminosities via the calibration from Fleming et al. (1995) and place age limits from these X-ray luminosities via Mamajek & Hillenbrand (2008; Equation A3). TOI-1807 has an X-ray luminosity of $\log L_X/L_{bol} = -4.53 \pm 0.24$, and an estimated 3σ age lower limit of $>19$ Myr. Similarly, TOI-2076 has an X-ray luminosity of $\log L_X/L_{bol} = -4.49 \pm 0.16$, corresponding to a 3σ age lower limit of $>18$ Myr.

Similarly, chromospheric emission in the cores of the Ca II lines are also qualitatively informative on the ages of systems. There is significant core emission in the Ca II H and K lines, as well as in the Ca II infrared triplet lines from the TRES spectra of TOI-1807 and TOI-2076.

Using the calibrations provided in Zhou et al. (2021), we measured equivalent widths for the core emission in the Ca II H&K lines and convert them to the Mount Wilson Observatory HK Project (Vaughan et al. 1978; Wilson 1978; Duncan et al. 1991; Baliunas et al. 1995) $S_{HK}$ indices for both target stars. We measure $S_{HK} = 1.008 \pm 0.074$ and $S_{HK} = 0.776 \pm 0.090$ for TOI-1807 and 2076 respectively; these were converted to the bolometric flux ratios of $\log R^c_{HK} = -4.409 \pm 0.033$ and $\log R^c_{HK} = -4.271 \pm 0.056$, respectively.

Like X-ray, the level of Ca II core emission is related to the rotation, and therefore age, of the target stars. We make use of the calibration offered by Mamajek & Hillenbrand (2008, their Equation (3)) to yield 3σ age ranges of 60–1800 Myr for TOI-1807 and 12–870 Myr for TOI-2076.

Similarly, we also follow Zhou et al. (2021) and measured the levels of core emission in the Ca II infrared triplet lines, finding equivalent widths of 0.36 ± 0.01 Å for TOI-1807 and 0.33 ± 0.01 Å for TOI-2076. Using the qualitative relationships provided in Zerjal et al. (2017), these core emissions are consistent with stars with ages between 100 and 1000 Myr of age.

6.3. Lithium Absorption

Lithium is rapidly depleted in the envelope of Sun-like stars within the first few hundred million years post-formation, as it is convectively mixed into the core and destroyed through proton collisions. The lithium 6708 Å line is therefore often a reliable and easily accessible indicator of youth for young Sun-like stars. Both TOI-1807 and TOI-2076 exhibit significant lithium absorption features. We measured Li 6708 Å equivalent widths for these target stars using the high-resolution observations from the TRES facility, as per the techniques described in Zhou et al. (2021), with equivalent widths of 0.0841 ± 0.0007 Å and 0.0703 ± 0.0071 Å for TOI-1807 and 2076, respectively.

Figure 11 places the lithium absorption strength measured for TOI-1807 and 2076 in context with other well-characterized clusters. As the lithium absorption strength is dependent on a large number of additional factors, such as rotational evolution and metallicity, we do not derive quantitative ages from the equivalent-width measurements. It is clear, however, that these target stars have ages significantly younger than stars in the 800 Myr old Praesepe cluster and significantly older than the 50 Myr old clusters IC 2602 and IC 2391.
7. Discussion

The planets transiting TOI-1807 and TOI-2076 are valuable benchmarks for studying the evolution of small planets. Transiting planets around young (<1 Gyr) stars are still relatively rare, and it remains to be seen if this is due to the scarcity of young stars amenable to transit searches, an age dependence to detection efficiency and/or planet occurrence rates, a lack of precise and accurate ages for planet hosts, or some combination of these effects.

An especially compelling use case provided by young transiting planets is the possibility of constraining models of radial contraction and atmospheric loss (e.g., Lopez & Fortney 2013; Owen & Wu 2013; Jin et al. 2014; Chen & Rogers 2016; Ginzburg et al. 2016). For example, one challenge in modeling the atmospheric evolution of planets with a photoevaporation model is the unknown X-ray and extreme ultraviolet (XUV) evolution of the host star (e.g., Kubyshkina et al. 2019a, 2019b; Owen & Campos Estrada 2020). This is because uncertainties in the time-integrated XUV exposure of a given planet are larger for stars with older and less precise ages, which could have had a wide range of XUV luminosities early in their lives. The X-ray and UV luminosities of nearby, young planet hosts can be directly measured and, provided some knowledge of the stellar age and planetary masses, allow for detailed modeling of the past (e.g., Owen 2020) and future (e.g., Poppenhaeger et al. 2021) evolution of a planetary system.

In this context, the most intriguing observations about the TOI-2076 system are the relatively large planet sizes, the possibility of constraining models of radial contraction and atmospheric loss (e.g., Lopez & Fortney 2013; Owen & Wu 2013; Jin et al. 2014; Chen & Rogers 2016; Ginzburg et al. 2016). For example, one challenge in modeling the atmospheric evolution of planets with a photoevaporation model is the unknown X-ray and extreme ultraviolet (XUV) evolution of the host star (e.g., Kubyshkina et al. 2019a, 2019b; Owen & Campos Estrada 2020). This is because uncertainties in the time-integrated XUV exposure of a given planet are larger for stars with older and less precise ages, which could have had a wide range of XUV luminosities early in their lives. The X-ray and UV luminosities of nearby, young planet hosts can be directly measured and, provided some knowledge of the stellar age and planetary masses, allow for detailed modeling of the past (e.g., Owen 2020) and future (e.g., Poppenhaeger et al. 2021) evolution of a planetary system.

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7. Discussion

The planets transiting TOI-1807 and TOI-2076 are valuable benchmarks for studying the evolution of small planets. Transiting planets around young (<1 Gyr) stars are still relatively rare, and it remains to be seen if this is due to the scarcity of young stars amenable to transit searches, an age dependence to detection efficiency and/or planet occurrence rates, a lack of precise and accurate ages for planet hosts, or some combination of these effects.

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In this context, the most intriguing observations about the TOI-2076 system in the broader context of multiplanet systems, respectively. While we cannot prove a causal link, it is intriguing that the TOI-2076 system extends the trend of large planetary radii observed in other young systems.

TOI-1807b is particularly interesting as it belongs to a distinct class of planets known as ultra-short-period planets (USPs; see Winn et al. 2018, for a review). USPs are intrinsically rare, with an occurrence rate of \( \lesssim 0.5\%–1\% \) around G- and K-type stars (Sanchis-Ojeda et al. 2014; Steffen & Coughlin 2016). Despite being about equally as rare as hot Jupiters, USPs are almost certainly unrelated to their more massive and distant cousins: they lack a strong preference for metal-rich hosts (Winn et al. 2017); they almost always occur in compact multiplanet systems (Sanchis-Ojeda et al. 2014; Adams et al. 2020), and they are more common around lower-mass stars (Sanchis-Ojeda et al. 2014). All of these trends run counter to what has been established for hot Jupiters. That being established, USPs may well be the remnant cores of sub-Neptunes.

Several lines of evidence suggest that USPs, including TOI-1807b, did not form in their current orbits, likely underwent inward migration, and are the result of nonstandard evolution. This evidence includes (1) present-day USP orbits lying interior to the dust sublimation radii of typical protoplanetary disks (e.g., Muzerolle et al. 2003; Eisner et al. 2005), (2) the observed period ratios between USPs and neighboring planets are much larger than the period ratios typically observed in multitransiting systems (Steffen & Farr 2013), (3) the planet occurrence rate is a steeper function of period inside 1 day relative to the rates in the 1–10 day or 10–100 day range (Lee & Chiang 2017), (4) USPs occur in multiplanet systems with larger-than-average mutual inclinations (Dai et al. 2018), and (5) well-characterized USPs are always smaller than 2 \( R_{\text{eq}} \), having densities consistent with rocky compositions (Dai et al. 2019). The size cutoff of USPs is seen as potential evidence that some experienced atmospheric loss.

Millholland & Spalding (2020) provided a recent review of the most promising theories for how USPs arrived on their observed orbits, all of which involve tidal dissipation and the accompanying orbital decay. Briefly, these theories can be summarized as (1) in situ formation near the inner edge of the protoplanetary disk, followed by tidal dissipation in the star (Lee & Chiang 2017), and (2) planet–planet interactions followed by tidal dissipation in the planet driven by either the planet’s orbital eccentricity (Schlaufman et al. 2010; Petrovich et al. 2019; Pu & Lai 2019) or the planetary obliquity (the angle between the planet’s spin axis and orbital angular momentum vector; Millholland & Spalding 2020). The latter class of theories naturally account for the high planet multiplicity and mutual inclinations in USP systems.

![Figure 12](image-url)\footnote{Figure 12. Probability distribution functions (top row) and cumulative distribution functions (bottom row) for the average planet size (left column) and the sum of planet sizes in confirmed multitransiting systems around GK stars.}
As the youngest USP detected to date, TOI-1807b places
stringent limits on theories for the formation and evolution of
these rare planets. The discovery of a USP around a young star
is compatible with a fast formation channel, which is also
suggested by a comparison of galactic velocity dispersions
between USP hosts and field stars (Hamers & Schlaufman 2020).
If stellar activity can be mitigated, RV follow up of TOI-1807
should lead to the discovery of the additional nontransiting
planets that likely exist; this would help piece together a
coherent picture of the past dynamics of the system that may
have driven TOI-1807b inwards.

To place TOI-1807b in a broader observational context, we
computed the JWST Emission Spectroscopy Metric (ESM; Kempton et al. 2018) for all confirmed USPs ($P < 1$ day,
$R_p < 2 R_\text{Jup}$) on the NASA Exoplanet Archive, assuming the Bond
albedo of Earth ($A_B = 0.306$). We found that TOI-1807b is the
third most favorable USP for the detection of mid-IR thermal
emission (Table 6 and Figure 13). Notably, the two planets that
rank more favorably, 55 Cnc e and LHS 3844 b, have securely
detected mid-IR phase curves and secondary eclipses (Demory et al. 2016; Kreidberg et al. 2019) while K2-141 b, which ranks
below TOI-1807b, has a detected phase curve and secondary
eclipse from K2 optical photometry (Malavolta et al. 2018).

Thus, the TOI-1807 system offers an opportunity to study a
small, likely rocky planet shortly after its formation and perhaps
after recently losing its atmosphere. The youth of TOI-1807b
makes it an even more compelling target for secondary eclipse
spectroscopy, as the luminosity of the planet’s cooling core may
be an order of magnitude higher than it would be at older
($>1$ Gyr) ages (Linder et al. 2019). Finally, as a candidate “lava
world” (Chao et al. 2020), TOI-1807b presents an opportunity
to study the early evolution of these poorly understood objects.

TOI-2076 and TOI-1807 are coeval and comoving; these young
stars likely formed together, though their large physical separation
(<9 pc) suggests they are not bound. Theoretical studies show that
very close stellar companions can have a significant effect on
planet formation; close companions can (1) truncate the
protoplanetary disk, preventing planetary formation (Jang-Condell 2015), (2) trigger the migration of giant planets, (3) eject smaller
planets, and (4) disperse the disk before or during planetary
formation (Cieza et al. 2009). Systems as widely separated as these
two stars essentially evolve as single stars, and we know little of
their formation processes and any interrelationship that may be
present. The detection of transiting planets in both TOI-2076 and
TOI-1807 reveals that the planetary orbital planes are co-aligned,
which hints at a common formation process whereby the both components maintain a nearly edge-on inclination to our line of

| Planet Name | ESM |
|-------------|-----|
| 55 Cnc e    | 101.0 |
| LHS 3844b   | 51.4  |
| **TOI-1807b** | **36.9** |
| GJ 1252b    | 26.6  |
| LTT 3780b   | 23.3  |
| K2-141b     | 21.5  |
| HD 3167b    | 20.0  |
| LP 791-18b  | 12.2  |
| TOI-561b    | 11.5  |
| K2-131b     | 9.7   |

Figure 13. The Emission Spectroscopy Metric (ESM) and Transmission
Spectroscopy Metric (TSM) from Kempton et al. (2018) for the sample of
confirmed, young, transiting exoplanets (gray), highlighting TOI-2076 and
TOI-1807. Points are scaled to represent the relative sizes of each planet. Top:
ESM as a function of stellar age, not accounting for any residual heat due to
formation. TOI-1807 shows a high signal-to-noise value, pointing to a possible
detectable secondary eclipse, despite TOI-1807b being a small planet. Bottom:
TSM as a function of age. All planets show a high TSM compared to other
known young transiting planets, indicating these are excellent candidates for
follow up with JWST.

7.1. Opportunities for Follow-up Observations

We have reported the detection and validation of TOI-2076b/c/d and TOI-1807b. These systems are extremely
valuable to the community. The youth of the host stars place
TOI-2076 and TOI-1807 in a valuable parameter space. The
proximity of the host stars (40 pc) could make these targets
excellent candidates for follow up with direct imaging surveys
to search for longer-period companions.

The bright, small host stars also provide an unparalleled
opportunity to observe small, young planets in both transmission
and emission using the James Webb Space Telescope (JWST)
close to a crucial transition age in planet formation. Figure 13 shows the ESM and Transmission Spectroscopy
Metric (TSM) from Kempton et al. (2018) for the current
sample of confirmed, young transiting planets.51 The ESM

51 https://exoplanetarchive.ipac.caltech.edu/, accessed 2021 January.
provides an estimate of the signal-to-noise ratio of a secondary eclipse in JWST’s MIRI LRS bandpass, and the TSM provides the signal-to-noise ratio of a 10 hr observation in JWST’s NIRISS, not accounting for the presence of clouds. These values do not account for any residual energy from planet formation and only account for the atmosphere signal due to heating at the equilibrium temperature of the planet. TOI-2076 and TOI-1807 are highlighted. We note that (1) there are few known transiting planets close to the ~100 Myr age, (2) TOI-1807b has the most observable emission of any small, young planet, and (3) TOI-2076b, TOI-2076c, TOI-2076d, and TOI-1807b are all excellent candidates for transmission spectroscopy with JWST, providing enough signal to noise for an atmosphere detection with just one transit.

One crucial step toward effective atmospheric characterization is obtaining mass measurements for the planets. The brightness of TOI-2076 and TOI-1807 makes them amendable to ground-based RV follow up, though the significant stellar activity may make detection more difficult. As a first-order guess, we estimate the planet masses using the probabilistic radius-to-mass conversion from Chen & Kipping (2017) and calculate the expected RV semiamplitude for a zero-eccentricity orbit. This yields an expected semiamplitude $K = 2.9^{+2.3}_{-0.8} \text{ m s}^{-1}$ for TOI-1807b and $K = 3.2^{+3.2}_{-1.2} \text{ m s}^{-1}$ for TOI-2076b. The RV signal strength is even less certain for TOI-2076c and TOI-2076d due to their unknown orbital periods, but based on the likely periods given in Section 3.6, their RV semiamplitudes should be on the order of $3-4 \text{ m s}^{-1}$ as well.

Because both targets are young and active stars, they are likely to exhibit RV jitter on order of 10 s–100 s of m s$^{-1}$, well in excess of the photon noise limit for a typical RV spectrograph (Luhn et al. 2020). The primary challenge in measuring the planet masses through RV is then mitigating the stellar activity, particularly because it is likely to be larger in amplitude than the Doppler signal. In this sense TOI-1807b is the most promising target for mass follow up, as its ultra-short orbital period suggests that the Keplerian signal will be separable from activity at the rotation period of the star. As demonstrated by recent Rossiter–McLaughlin (RM) effect measurements on very young and active stars, it is feasible to measure short-duration RV signals on timescales of hours even in the presence of high-amplitude stellar variability on longer timescales of days (Montet et al. 2020; Zhou et al. 2020). RV follow up of TOI-2076b/c/d will be more challenging because the planetary orbital periods are comparable to the stellar rotation, and the complexity of the multiplanet RV signal requires a larger number of observations. That being said, recent work on other young systems like K2-100 and au Mic has effectively employed stellar activity models to extract RV constraints in the face of considerable activity (Barragán et al. 2019; Klein et al. 2021), and these targets are prime examples of the importance of developing such methods.

We note also that similar RV amplitudes are expected for the RM effect of these planets. The spin–orbit alignment measurement enabled by RM measurements would be particularly valuable for constraining the formation and migration histories of these planets. TOI-2076c is expected to be the best RM target, with an amplitude on the order of $10 \text{ m s}^{-1}$ (Triaud 2018), possibly within reach of modern observations. This amplitude is not sensitive to the unknown orbital period of the planet, although refined ephemerides will of course be necessary to obtain the required in-transit observations.

A previous study of USP planets by Sanchis-Ojeda et al. (2014) concluded that they often have longer-period coplanar companions in the period range of $\leq 50$ days. Because the transit probability of USP planets in these multiplanet systems is significantly higher than that of the longer-period companions, systems with a single transiting USP planet are likely to also have nontransiting outer planets. While we identified no longer-period transiting planets in the TOI-1807 system, RV measurements of TOI-1807, and perhaps future direct imaging observations, may reveal additional planets in this system.

Although the known planets detected in transit are too close to their stars to be directly imaged, giant planets in the outer reaches of the TOI-2076 and TOI-1807 systems may be more detectable. Due to the young age of the stars, giant planets would still be cooling from formation and would therefore appear brighter at infrared wavelengths than mature Jovian planets (e.g., Burrows et al. 1997). Depending on their masses, ages, formation conditions, and cooling rate, massive Jovian planets orbiting TOI-2076 and TOI-1807 at separations comparable to Saturn, Uranus, or Neptune (10–30 au) could be within reach of current and upcoming instruments (e.g., Bowler 2016; Lacy & Burrows 2020).

### 8. Conclusions

In this paper we have presented and validated two systems of planets around two young, comoving stars. These planets could provide a unique opportunity for further study by characterizing atmospheres in transmission, emission, and phase curves in the immediate future. The host-star variability may make RV observations challenging, but in the case of TOI-1807b we expect mass measurements to be accessible. Their close proximity to earth could make them excellent candidates for direct imaging. In the case of the USP TOI-1807b, we may expect further, long-period planets to be present. The potential for a joint formation history of these two host stars makes them a unique opportunity to intercompare planet systems with the same starting conditions but different outcomes. We suggest TOI-2076 and TOI-1807 are exceptional candidates for further follow up and to further our understanding of young planets.

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52 http://www.astropy.org
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