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A Second Planet Transiting LTT 1445A and a Determination of the Masses of Both Worlds

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Abstract

LTT 1445 is a hierarchical triple M-dwarf star system located at a distance of 6.86 pc. The primary star LTT 1445A (0.257 $M_\odot$) is known to host the transiting planet LTT 1445Ab with an orbital period of 5.36 days, making it the second-closest known transiting exoplanet system, and the closest one for which the host is an M dwarf. Using Transiting Exoplanet Survey Satellite data, we present the discovery of a second planet in the LTT 1445 system, with an orbital period of 3.12 days. We combine radial-velocity measurements obtained from the five spectrographs, Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, High Accuracy Radial Velocity Planet Searcher, High-Resolution Echelle Spectrometer, MAROON-X, and Planet Finder Spectrograph to establish that the new world also orbits LTT 1445A. We determine the mass and radius of LTT 1445Ab to be $2.87 \pm 0.25 ~M_\oplus$ and $1.304^{+0.067}_{-0.060} ~R_\oplus$, consistent with an Earth-like composition. For the newly discovered LTT 1445Ac, we measure a mass of $1.54^{+0.20}_{-0.15} ~M_\oplus$ and a minimum radius of $1.15 ~R_\oplus$, but we cannot determine the radius directly as the signal-to-noise ratio of our light curve permits both grazing and nongrazing configurations. Using MEarth photometry and ground-based spectroscopy, we establish that star C (0.161 $M_\odot$) is likely the source of the 1.4 day rotation period, and star B (0.215 $M_\odot$) has a likely rotation period of 6.7 days. We estimate a probable rotation period of 85 days for LTT 1445A. Thus, this triple M-dwarf system appears to be in a special evolutionary stage where the most massive M dwarf has spun down, the intermediate mass M dwarf is in the process of spinning down, while the least massive stellar component has not yet begun to spin down.

1. Introduction

Terrestrial exoplanets are difficult to study. Whether one is seeking to measure their bulk densities, search for attendant satellites, or probe their atmospheres, the task is made easier by two factors. First, the host stars must be nearby, so that we might mitigate the cruel dictates of the inverse square law. Second, the stellar mass and radius should be small, so that the ratio of the planetary and stellar quantities is maximized. It is for these reasons that nearby M-dwarf systems are the darlings of the exoplanet menagerie. Fortunately, M dwarfs are abundant, making up approximately 72% of all stars in the stellar neighborhood (Henry et al. 2018). Their dominance among nearby planetary hosts is likewise in evidence. Indeed, of the 16 stars within 15 parsecs that are known to host transiting exoplanets, all but 4 are M dwarfs.

At a distance of 6.53 pc, the closest star known to host transiting exoplanets is HD 219134 (Motaleti et al. 2015; Gillon et al. 2017). Although the two transiting worlds have had their densities measured, they are otherwise largely inaccessible because the parent star is a K dwarf with a radius of 0.778 $R_\odot$. However, the star in second place is much more diminutive in stature: LTT 1445A, with a radius of 0.268 $R_\odot$ and a mass of 0.257 $M_\odot$. At a distance of 6.86 pc (Gaia Collaboration et al. 2016; Lindegren et al. 2021), it is the closest M dwarf known to host a transiting planet. Using data from the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) and a host of ground-based telescopes, Winters et al. (2019, hereafter W19), published the discovery of LTT 1445Ab, a planet with an orbital period of 5.36 days. Although that planet was presumed to be terrestrial owing to its radius, no measurement of its mass has yet been presented. A mass measurement is crucial for at least two reasons. First, it would constrain the bulk composition of the planet. If the planet proves to be terrestrial, the mass measurement would allow for the determination of the ratio of its iron-and-nickel core to its magnesium-silicate mantle, which in turn could be compared to elemental abundances of the stellar photosphere. Second, future atmospheric studies require a direct estimate of the surface gravity to enable an unambiguous interpretation of data gathered in transmission, as the atmospheric scale height is a combination of the surface gravity, temperature, and mean...
molecular weight. Intriguingly, LTT 1445A is the most massive member of a resolved triple M-dwarf system. The three stars fall on a line (see Figure 1 from W19), and the stellar orbital plane of stars B and C is viewed edge-on, and hence the entire system may be coplanar.

In pursuit of the mass of LTT 1445Ab, we set out to gather multiepoch radial-velocity (RV) measurements with five high-resolution spectrographs. While that activity was underway, we found a second periodic transit-like signal in the TESS data. Combining the RV and TESS data with ground-based photometric monitoring, we established that indeed a second planet transits LTT 1445A and orbits interior to the known world. In what follows, we describe these findings, along with our measurements of the masses of both worlds.

We briefly summarize the host star system in Section 2, before turning to a description of our photometric and spectroscopic data in Section 3. We present our analysis of these data in Section 4 and their implications in Section 5.

2. Description of the Host Stellar System

The host system, LTT 1445ABC\(^66\) (Luyten 1957, 1980), is a nearby, hierarchical trio of mid-to-late M dwarfs. The preliminary astrometric orbit for LTT 1445BC, presented in W19, indicates an orbital period of 36.2 ± 5.3 yr and a semimajor axis 1.159 ± 0.076, which corresponds to an average physical separation of 8.1 ± 0.5 au. As noted in W19, the separation between A and BC appears to have recently begun decreasing, with the most recent value of 7″10 obtained in 2017, according to data available in the Washington Double Star (WDS) Catalog\(^67\) (Mason et al. 2009). Considering the total mass of the three stellar components and an average angular separation of 5″ (corresponding to 34 au, calculated using the weighted mean of the parallaxes of A and BC: 145.6917 ± 0.0244 mas), we estimate the period of the A–BC orbit to be roughly 250 years. We refer the reader to Figure 1 in W19, which presents a resolved image of the three stars in the system. We also refer the reader to Table 1 in W19, which lists the astrometry, photometry, and stellar parameters of LTT 1445.

3. Observations

3.1. Photometric Time Series Data

We describe here the photometric time series observations of LTT 1445 by TESS, the MEarth-South telescope array, and the Las Cumbres Observatory telescope network.

3.1.1. TESS Observations

TESS observed LTT 1445 in the first year of its prime mission, which resulted in the discovery of LTT 1445Ab, as described in W19. We included this system in our TESS Guest Investigator program (PI Winters; G03250) target list to gather short-cadence (two-minute) data of the volume-complete sample of M dwarfs with masses 0.1 < \(M/M_\odot\) < 0.3 within 15 pc (Winters et al. 2021). LTT 1445A and BC were also included in the TESS Input Catalog (TIC) and Candidate Target List (CTL; Stassun et al. 2018) via the Cool Dwarf

\(^66\) Other names for A: TIC 98796344, TOI 455, L 730-18, BD-17 588A, RST 2292A, WDS J03019-1633A, 2MASS J03015142-1635356, Gaia DR2 J03153091836072107136, GJ 3193; other names for BC: TIC 98796342, BD-17 588B, RST 2292BC, WDS J03019-1633B, 2MASS J03015107-1635306, Gaia DR2 J03153091836072107008.

\(^67\) https://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/WDS
Sample (Muirhead et al. 2018). The LTT 1445 system was reobserved at two-minute cadence in sector 31 from UT 2020 October 22 to November 16, in spacecraft orbits 69 and 70. The system fell on CCD 4 of Camera 2.

As described in the data release notes68 for sector 31, data collection was paused for 1.4 days between the two orbits to download data, a single momentum dump was conducted halfway through each orbit, and a star tracker anomaly caused the data collection in orbit 70 to end 2.08 days early.

The two-minute cadence data were reduced with the NASA Ames Science Processing Operations Center (SPOC) pipeline (Jenkins et al. 2015, 2016) that was repurposed from the Kepler reduction pipeline (Jenkins et al. 2010). A planet candidate with an approximate radius of $1.5 \pm 0.4 R_{\oplus}$ was again detected in four transits during sector 31 to have a period of 5.36 days and a transit depth of $2750 \pm 191$ ppm with a signal-to-noise ratio of 15.2.

A second planet with a 3.12 day period and a transit duration of roughly 45 min was identified in the sector 4 light curve of LTT 1445 by several of us (MHK, IAT, HMS, MO, AS). After the release of the sector 31 light-curve data, we recovered a very shallow transit signal with a period of $P = 3.12$ days. This second planet has not been identified by the TESS planetary- vetting team, and is thus not assigned a TOI designation; however, the TESS SPOC algorithm recovered signals at periods of 1.5623 days and 1.5616 days, half that of the 1.4 day signal in the MEarth light curve of LTT 1445 BC is highly variable over long time baselines, predominantly due to wind shake. Wind at the location of MEarth-South on Cerro Tololo shows a seasonal variation, with stronger and more gusty winds during the winter and spring seasons in particular. FWHM values ranging from approximately 1.7–5.3 pixels were recorded during the time series, where the pixel scale is 0.84 arcsec/pixel. Consequently, while the BC pair is always blended, there is variable blending between A and BC, requiring specialized photometric extraction procedures.

As described in W19, separate apertures of 4.2 pixels in radius were placed on the A and BC components, using a global (full-field) astrometric solution for aperture positioning to avoid drift in the relative positions of the A and BC apertures as a function of the image quality. For the present purpose, we require separate light curves of A and BC, so external comparison stars elsewhere in the field were used rather than the procedure used for the transit follow-up observations in our previous work. The LTT 1445 system is in a sparse field so there were relatively few of these available, and they are fainter than the target stars. Thus, the resulting photometric solutions exhibit higher noise levels and systematic errors than are typical for MEarth data.

The comparison star solutions are unable to correct the effect of variable blending between A and BC, which causes fairly severe systematic errors in the resulting light curves. In order to partly correct this effect, we modified our standard techniques used for periodogram analysis of MEarth data detailed in Newton et al. (2016) to use simultaneous linear decorrelation against both the standard “common mode” term (to correct variable atmospheric precipitable water vapor) and against the FWHM.

The resulting periodograms are shown in Figure 1, where we compare results for the TESS light curve containing all three components with the separate MEarth light curves for A and BC. We also show the periodogram of the observational window function in each case.

The periodogram is plotted in terms of the F-test statistic for the nested model comparison between the null hypothesis of only the baseline detrending with no rotation signal, and the alternate hypothesis where there is also a sinusoidal signal of the given period (further details of this procedure are given in Newton et al. 2016). At a fixed period, this statistic would follow an $F$ distribution $F(2, \nu)$ where the number of degrees of freedom $\nu$ is large. Standard results for this distribution show the 1.4 day signal in the MEarth light curve of LTT 1445 BC is highly significant with an $F$ value several hundred above the baseline level in the periodogram.
The 1.4 day signal detected in TESS data and reported previously by W19 is found to originate from BC, as expected based on stellar activity and rotational broadening results presented in the previous paper, but this has now been resolved observationally. The 1 day −1 alias of this signal is also seen close to 3.5 days. No clear rotational modulation signal meeting our quality criteria (see Newton et al. 2016) is yet detected in LTT 1445A, but the periodogram shows power at long periods between approximately 40 and 150 days and the corresponding alias period close to 1 day. Based on the observed activity level and mass of this star, a rotation period around 85 ± 22 days would be expected (calculated using the empirical relation in Newton et al. 2017) but has yet to be detected in the observations. We show the MEarth light curves for LTT 1445A and BC in Figure 2.

3.1.3. MEarth-South Transit Follow-up Observations

We also performed follow-up observations with MEarth-South spanning times of the transit of planet b. Because MEarth is able to spatially resolve star A from stars BC, these data serve to confirm that planet b indeed transits star A. As discussed above in Section 3.1.2, MEarth observations of the LTT 1445 system are extremely sensitive to image quality due to the components being barely resolved in the data. Additionally, due to the short exposure time, atmospheric scintillation noise is severe and increases with airmass. Consequently, although we observed several transits of LTT 1445Ab for follow up, the majority of these were poor quality, and all but one were rejected for the final analysis.

Our analysis includes a single full transit observed on UT 2019 September 2 using seven telescopes. Otherwise, the observational strategy and reduction techniques were identical to those described in W19 and are not repeated here. A total of 3935 data points were gathered during this time series, and the resulting light curve is shown in the top panel of Figure 3.

Because the expected transit depth of the 3.12 day planet candidate was below the detection limits of the MEarth array, we did not attempt observations to confirm it with MEarth.

3.2. LCOGT Transit Follow-up Observations

We observed three full transits of LTT 1445Ab from the Las Cumbres Observatory Global Telescope (LCOGT; Brown et al. 2013) 1.0 m network. We observed a full transit on UT 2019 August 16 in the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) Y-band from the CTIO node using 30 s exposures, and a full transit on UT 2020 October 8 in the Pan-STARRS z-short band from the McDonald Observatory node using 10 s exposures. A full transit was observed on UT 2019 July 16 from the South Africa Astronomical Observatory node in the Pan-STARRS Y-band using 30 s exposures. However, we ultimately chose not to include this observation in the analysis because only a few minutes of nominal posttransit baseline were observed, resulting in an unclear time of egress and thus a depth measurement that is not well constrained. We used the TESS Transit Finder, a customized version of the Tapir
software package (Jensen 2013), to schedule our transit observations. The 4096 × 4096 LCOGT SINISTRO cameras have an image scale of 0.2839 per pixel, resulting in a 26′ × 26′ field of view. The images were calibrated by the standard LCOGT BANZAI pipeline (McCully et al. 2018), and photometric data were extracted with AstroImageJ (Collins et al. 2017). The UT 2019 August 16 images were (unintentionally) mildly defocused and had typical stellar point-spread-functions with a FWHM of roughly 3″. Circular apertures with radius of roughly 2″ were used to extract the differential photometry. We estimate that about 2% of the flux in the target star aperture is from the nearby pair LTT 1445BC. The UT 2020 October 8 images were very slightly defocused and had typical stellar point-spread-functions with a FWHM of roughly 3″. Circular apertures with radius of roughly 2″ were used to extract the differential photometry. We estimate that about 1.3% of the flux in the target star aperture is from the nearby pair LTT 1445BC. For all observations, we used a single comparison aperture around the nearby pair LTT 1445BC to extract the light curve of LTT 1445Ab. The light curves are presented in the bottom panel of Figure 3.

Using the LCOGT 1.0 m network and an ephemeris extracted from TESS sector 4 data, we attempted to recover the 3.12 day transit signal on six epochs in 2019 and 2020. However, the updated ephemeris based upon the combination of the sector 4 and 31 data shows that those observations were typically 5 hr late and do not span the times of transit.

3.3. Spectroscopic Data

We combined 136 RVs of LTT 1445A from five high-resolution spectrographs taken over roughly two years. Here we describe the instruments in alphabetical order, as well as the methods used to measure the RVs and their uncertainties. We list the RVs and their uncertainties in Table 1.

### Table 1
Radial Velocities for LTT 1445A

| BJD<sup>a</sup> (days) | \( v_{rad}<sup>b</sup> \) (m s<sup>-1</sup>) | \( \sigma \) (m s<sup>-1</sup>) | Spectrograph |
|------------------------|-----------------|-----------------|----------------|
| 2458546.50296          | −5457.74        | 1.31            | HARPS          |
| 2458547.501338         | −5463.53        | 1.16            | HARPS          |
| 2458548.500633         | −5460.85        | 1.16            | HARPS          |
| 2458555.506869         | −5455.18        | 1.29            | HARPS          |
| 2458556.505906         | −5453.54        | 1.16            | HARPS          |

Notes.

<sup>a</sup> Barycentric Julian Date of mid-exposure, in the TDB time-system.

<sup>b</sup> Barycentric radial velocity.

(This table is available in its entirety in machine-readable form.)

Thus, the calibration fiber was set on sky. The S/N of the spectra ranges between 58 and 142 at 650 nm, with an average of 104.

We derived the RVs using the \( \chi^2 \)-minimization template-matching method described in Astudillo-Defru et al. (2015). The stellar template was built from the median of the individual spectra, accounting for the ESPRESSO design that creates two individual images (slices) of the same spectral order. To compute the RVs, we discarded echelle orders below order 15 (30 slices) due to the low flux, as well as zones containing telluric features. RV uncertainties were computed following the methods described in Bouchez et al. (2001) and range between 0.15 m s<sup>-1</sup> and 0.32 m s<sup>-1</sup>, with an average uncertainty of 0.20 m s<sup>-1</sup>.

### 3.3.2. HARPS

We acquired 45 spectra of LTT 1445A with the High Accuracy Radial Velocity Planet Searcher (HARPS) spectrograph (Mayor et al. 2003) on the La Silla 3.6-m telescope from UT 2019 March 04 to October 21. HARPS is a fiber-fed echelle spectrograph with resolving power \( R = 115,000 \) and a wavelength range of 378-691 nm. We employed integrations times of 900 s, and the spectra were read out in slow mode (104 kpdx s<sup>-1</sup>), except for one spectrum acquired on 2019 September 12, which had an exposure time of 1500 s. We found that for seven of our spectra we had inadvertently observed the BC component, as evidenced by the Hα emission. We discarded these from the RV analysis, but these spectra later proved to be a blessing in disguise, as they allowed us to investigate the rotational broadening of the B and C components (see Section 4.5). The calibration fiber was set on sky. The science fiber provides S/Ns between 26 and 60 at 650 nm, with an average of 48. As with ESPRESSO, we derived the RVs by template matching, and we estimated the uncertainties following the methods of Bouchy et al. (2001); these range between 1.06 m s<sup>-1</sup> and 2.86 m s<sup>-1</sup>, with an average uncertainty of 1.44 m s<sup>-1</sup>. We allowed for a separate RV zero-point offset for the 2019 February data because of the roughly four-month time span between those data and the later observations.

We also measure the Ca II H and K emission (S activity index) and proceed to calculate a value of \( \log(R'_{HK}) = −5.413 ± 0.118 \). Following Astudillo-Defru et al. (2017), we estimate a rotation period of 79 ± 15 days, in agreement with the estimated rotation period of 85 ± 22 days noted above.

### 3.3.3. HIRES

We acquired 39 spectra of LTT 1445A with the High-Resolution Echelle Spectrometer (HIRES) on the 10 m Keck telescope on Maunakea, Hawai'i, on nights between UT 2019 August 14 and 2020 February 28. HIRES is an optical echelle spectrograph with resolving power \( R ≈ 55,000 \) (Vogt et al. 1994). We used the standard procedures of the California Planet Search (CPS; Howard et al. 2010) to make the observations and reduce the spectra. This includes the use of an iodine cell to calibrate the wavelength solution and point-spread function of HIRES, as well as a long slit (the “C2” decker) to measure and subtract contemporaneous sky spectra. We used an image rotator to orient the field so that light from LTT 1445A went through the slit, and light from LTT 1445BC did not. The HIRES spectra span the wavelengths 364–790 nm with our CPS setup, but the RVs were computed from the
wavelength range 500–630 nm because that region is calibrated by the iodine. We used integration times of 900 s, which resulted in S/Ns of 100–170 per pixel on blaze near 550 nm. We computed relative RVs using the method descended from Butler et al. (1996). The HIRES RVs have internal uncertainties between 1.3 m s\(^{-1}\) and 2.0 m s\(^{-1}\), with an average uncertainty of 1.5 m s\(^{-1}\).

3.3.4. MAROON-X

We used the MAROON-X spectrograph (Seifahrt et al. 2016, 2018, 2020) on the 8.1-m Gemini-North telescope to measure RVs of LTT 1445A during three observing runs of two weeks each between 2019 December and 2020 November. MAROON-X is a stabilized, fiber-fed echelle spectrograph with resolving power \(R \approx 85,000\) and a wavelength range of 500–920 nm in two camera arms. MAROON-X has demonstrated an RV stability of at least 30 cm s\(^{-1}\) over the span of a few weeks during its first year of operations (Seifahrt et al. 2020) and has recently been used to determine a precise mass of the nearby transiting rocky planet Gl 486b (Trifonov et al. 2021).

We acquired 27 spectra of LTT 1445A over eight nights during the science verification and commissioning phase of the instrument in 2019 December. The simultaneous calibration was not operational during these first observations, so bracketing wavelength calibration exposures were taken to track the instrumental drift. The lack of simultaneous calibration likely limits the instrumental precision of these data to approximately 1 m s\(^{-1}\). Moreover, we found that 7 of the 27 spectra in two consecutive nights in 2019 had low S/N and also showed abnormal chromatic index and differential line widths in MAROON-X’s blue arm. Some of these spectra lead to RV outliers and thus all seven spectra were subsequently dropped from the RV analysis. Due to their low S/N and thus larger individual RV uncertainty, their contribution to the nightly mean was small and did not significantly change the final RV data point for the night.

We gathered an additional 20 spectra over 17 nights in 2020 September and November. We find only a single night with notable stellar activity in this data set. Because the RV measurement from this one night does not present as a clear outlier, we included this data point in the RV analysis.

We used integration times of 600 s in 2019 and 300 s in 2020. In 2019, the peak S/N per 1D pixel ranges between 60 and 190 at 640 nm in the blue arm and between 140 and 430 at 800 nm in the red arm, with a widespread distribution depending on seeing conditions. In 2020, we find peak S/Ns ranging between 50 and 95 at 640 nm in the blue arm and between 130 and 250 at 800 nm in the red arm.

We reduced the MAROON-X raw data using a custom Python 3 pipeline based on tools previously developed for the Cryogenic Infrared Echelle Spectrograph (Bean et al. 2010). The wavelength and instrumental drift solution of MAROON-X is based on a stabilized Fabry–Perot etalon (Stürmer et al. 2017) in conjunction with a ThAr lamp for the initial measurement of the gap size and chromatic dispersion of the etalon. In early 2020, the simultaneous calibration fiber of MAROON-X became operational, allowing for a robust order-by-order drift correction at the sub–m s\(^{-1}\) level. Barycentric corrections were computed using the barycorrpy code (Kanodia & Wright 2018) from weighted averages based on MAROON-X’s white-light exposure meter.

We computed the RVs using serval (Zechmeister et al. 2018), which employs a \(\chi^2\)-minimization algorithm based on matching an empirical template to each order at each epoch. The template is constructed from the data set itself as a weighted average of all observations. A telluric mask is used to exclude telluric absorption features deeper than about 1%, both in the construction of the template and in each epoch. Typical uncertainties derived by serval are based on the interorder dispersion of the RVs and range from 0.25 m s\(^{-1}\) for the highest S/N of 430 in the red channel to 1.6 m s\(^{-1}\) for the lowest S/N of 60 in the blue channel. To increase the S/N for robust RV calculations, we combined blue and red arm observations as well as multiple back-to-back observations per night into nightly epoch means and propagated uncertainties based on the spread of the individual measurements. These final uncertainties range from 0.4 to 1.4 m s\(^{-1}\) in 2019 and 0.4 to 1.0 m s\(^{-1}\) in 2020, with an average uncertainty of 0.8 and 0.6 m s\(^{-1}\), respectively.

Because of an instrument intervention that took place after the 2019 commissioning run, which introduced changes to both the etalon as well as the spectral format of the blue arm, we treat the data from 2019 and 2020 as independent data sets with distinct RV offset parameters.

3.3.5. PFS

We acquired 25 spectra (15 when binned by night) of LTT 1445A with the Planet Finder Spectrograph (PFS; Crane et al. 2006, 2008, 2010), mounted on the 6.5 m Magellan II telescope at Las Campanas Observatory in Chile, from UT 2019 July 20 to 2020 November 4. PFS covers 391–734 nm, and the subsequent RVs are calibrated using the iodine method. The default 0′/3 slit provides a resolving power \(R = 127,000\). Integration times ranged from 960 to 1500 s resulting in S/Ns between 40 and 70 at the peak of the blaze around 600 nm. All PFS spectra are reduced and analyzed using a custom IDL pipeline based on Butler et al. (1996) that regularly delivers sub–m s\(^{-1}\) precision. We binned observations taken sequentially to improve the S/N for robust RV calculations. The RV uncertainties in our nightly binned RVs ranged between 0.48 m s\(^{-1}\) and 0.83 m s\(^{-1}\), with an average uncertainty of 0.63 m s\(^{-1}\).

4. Analysis

Because of the complex nature of the TESS light curve, we used a combination of exoplanet (Foreman-Mackey et al. 2017) and ExoFASTv2 (Eastman et al. 2019) for our light-curve modeling: We first used exoplanet to fit and remove the photometric modulation in the TESS light curve using a Gaussian Processes (GP) regression model via celerite while preserving the transit signals of the two planets. We then used ExoFASTv2, which does not use GPs, to simultaneously fit the RV data and the detrended transit data from exoplanet. We also performed an independent RV-only analysis that included a GP regression to account for stellar activity that could affect the uncertainties of the planetary masses.

We will know the masses and radii of these planets only as well as we know these values for their host star. We estimate a mass of 0.257 ± 0.014 \(M_\odot\) for the host star using the mass–luminosity relation in the \(K\) band by Benedict et al. (2016) and then use a single-star mass–radius relation (Boyajian et al. 2012).
to estimate a stellar radius of \(0.268 \pm 0.027 R_\odot\). We calculate the bolometric corrections in \(K\) (Mann et al. 2015) and in \(V\) (Pecaut & Mamajek 2013), along with their respective bolometric luminosities. We adopt the mean of the two bolometric luminosities and then use the Stefan–Boltzmann law to calculate an effective temperature \(T_{\text{eff}}\) of \(3337 \pm 150\) K for LTT 1445A. We adopt a metallicity [Fe/H] of \(-0.340 \pm 0.090\) dex from Neves et al. (2014), which is measured using HARPS data. We updated the parallax of LTT 1445A to that of the Gaia Early Data Release (EDR3; Gaia Collaboration et al. 2016; Lindegren et al. 2021) for our estimates of the star’s mass, radius, and effective temperature, but these values did not change significantly from those reported in W19. We use these stellar parameters of LTT 1445A as priors for the light curve and RV modeling described below.

4.1. Light-curve Modeling with exoplanet

The presence of other objects in the TESS aperture can dilute the transit depth of the planet, which is measured from the light curve. If the additional objects have identifiers and TESS magnitudes in the TESS Input Catalog (TICv8.1; Stassun et al. 2019), the SPOC pipeline calculates a dilution (i.e., contamination) factor and performs a correction to the final light curve (Stumpe et al. 2012). For the sector 4 data, the SPOC contamination value of 0.4849 is very close to our estimated value of 0.480 \(\pm 0.013\), which is calculated from \(T\) mags estimated from an M-dwarf-specific relation (W19). For the sector 31 light curve, the SPOC contamination value is 0.42003, which is significantly different. The difference is partly due to an updated \(T\) mag for LTT 1445A of \(T = 8.843\) mag in the TICv8.1, compared to \(T = 8.64\) mag from an earlier TIC version. However, the TICv8.1 also appears to have a duplicate entry for LTT 1445BC, one from the 2MASS cross match (TIC 98796342) with \(T = 8.554\) mag and the other from the Gaia DR2 cross match (TIC 65189442) with \(T = 11.558\) mag. Thus, the SPOC dilution value in the sector 31 light curve is an overestimate of the amount of contaminating light from the BC components. As in W19, we removed the SPOC dilution value and imposed our own.

As in W19, we did not include the third transit of LTT 1445Ab in sector 4 in our analysis because the light-curve baseline showed a strong slope at egress; we note that this transit was also omitted from the results in the SPOC DV report. The third transit of LTT 1445Ac in the sector 4 light curve was not observed, as it occurred during the communication failure. The fourth transit occurred during the brief chunk of light curve right before the data download. Our GP did not fit properly over such a small span of data, so in the interest of working with uniformly processed data, we omitted this transit from our analysis. The third transit of the 5.36 day planet in the sector 31 data occurred during the pause in data collection while the data were being downloaded and was thus not observed. The star tracker anomaly reported for sector 31 did not affect the transits of either planet.

We used the python package exoplanet (Foreman-Mackey et al. 2019), which employs probabilistic methods to model exoplanet transit and radial-velocity data sets. It has the additional capability to incorporate GP with celerite (Foreman-Mackey et al. 2017) and limb-darkened light curves with starry (Luger et al. 2018). We used the SPOC-generated Pre-Search Data Conditioning Simple Aperture Photometry (PDCSAP) light curve (Smith et al. 2012; Stumpe et al. 2012, 2014), corrected with our calculated dilution factor. Before fitting, we removed positive outliers (flares) that deviated by more than 3 times the median absolute deviation of the PDCSAP light curve. While we do not know from which star the flares originate, recent work on nearby mid-to-late M dwarfs (see, e.g., Medina et al. 2020) indicates that rapidly rotating stars flare far more frequently. Thus, we suspect that many of the flares originate from either or both of the B or C components.

We model the stellar rotational modulation, as well as any other possible systematics, with a GP. The GP kernel is the sum of two simple harmonic oscillators, which has been shown to be an appropriate kernel for data that are quasiperiodic in nature (Angus et al. 2018), such as the observed rotational modulation in the light curve of LTT 1445ABC. To model the planetary transits, we used a limb-darkened transit model and a Keplerian orbit. We used the same model, priors, GP hyperparameters, and methods for the fit as described in W19. We measure planet-to-star radius ratios of \(0.037 \pm 0.005\) and \(0.047 \pm 0.006\) for LTT 1445Ac and LTT 1445Ab in the TESS sector 4 light-curve data and ratios of \(0.035 \pm 0.009\) and \(0.042 \pm 0.007\) for the respective planets in the TESS sector 31 light-curve data.

We note that the 1.4 day rotation signal has evolved in the two years that elapsed between sector 4 and 31. While the period of the modulation is the same, the semi-amplitude of the variability has roughly doubled from \(1.475 \pm 0.302\) ppt in the sector 4 light curve to \(3.027 \pm 0.401\) ppt in the sector 31 light curve. This increase in the semi-amplitude is likely due to a change in the morphology of the starspot groups leading to a larger hemisphere-integrated asymmetry in sector 31. We show our GP fit to the TESS light-curve data for both sector 4 and 31 in Figure 4.

4.2. Global Modeling with ExoFASTv2

We perform a simultaneous global fit of the TESS light-curve and radial-velocity data using ExoFASTv2 (Eastman et al. 2019). ExoFASTv2 is a suite of IDL routines that simultaneously fits exoplanetary transit and radial-velocity data using a differential Markov Chain Monte Carlo (MCMC) code. We include the TESS light curves from sectors 4 and 31, and we use 134 RVs from the five spectrographs. We used as input for the ExoFASTv2 the output light-curve data from exoplanet with the stellar variability removed. In order to allow for the propagation of the uncertainty in the dilution that was corrected by the exoplanet fit, we allow for a residual dilution, with a prior centered on zero with \(\sigma = 0.013\).

Because we derived the stellar parameters as described in Section 2, we did not include a spectral energy distribution in the fit, and we disabled the default Modules for Experiments in Stellar Astrophysics (MESA) Isochrones and Stellar Tracks (MIST) stellar evolutionary models that use isochrones to constrain the stellar parameters. We placed Gaussian priors on the stellar mass, radius, effective temperature, and metallicity that were equal to the uncertainties noted above in Section 4. We interpolated the quadratic limb-darkening coefficients in Table 15 of Claret (2017) to the effective temperature of LTT 1445A, which we imposed with a Gaussian prior with a standard deviation of 0.10. While the atmospheric models used to derive the limb-darkening tables are questionable for low-mass stars such as LTT 1445A, the impact is likely to be negligible due to the low precision of the TESS light curve.
We include a slope term to account for a change in the RVs of LTT 1445A due to the stellar A–BC orbit. We estimated the magnitude of the RV slope as follows. Because the maximum change in RVs over the 643 day time span of our data is dependent upon the eccentricity of the orbit, we explored which eccentricities would result in a stable configuration for the A–BC orbit. The stability criterion for hierarchical triple star systems from Harrington (1972) requires the eccentricity of the outer (A–BC) orbit and the ratio of the semimajor axes of the inner (B–C) and outer orbits. We investigated eccentricities 0 to 0.9 and semimajor axes of 1″ (from the preliminary astrometric orbit for LTT 1445BC reported in Winters et al. 2019) and 5″ (the mean separation noted for LTT 1445A-BC in Section 2), respectively, to estimate that retrograde motion orbits with eccentricities less than 0.45 would be stable. Therefore, we estimate that an orbital period of 253 yr for LTT 1445A-BC would result in a drift in our RV data with values between 0.0002 m s\(^{-1}\) day\(^{-1}\) for a circular orbit to 0.25 m s\(^{-1}\) day\(^{-1}\) for an eccentric (\(e = 0.45\)) orbit. We ran two separate ExoFASTv2 fits, one that included the term for the slope, and one that did not. ExoFASTv2 provides statistical metrics, such as the Bayesian Information Criterion (BIC; Schwarz 1978) and Akaike Information Criterion (AIC; Akaike 1974), for model fits. Both metrics are functions of the number of parameters being fit and the maximum ln(likelihood) from the MCMC sample, while the BIC also considers the number of data points being fit. The better model has the smallest algebraic value of AIC or BIC. The fit that included the slope term for the RVs was slightly preferred over the flat RV fit, with BIC and AIC values of −22,202 and −22,424, respectively, for the model with no slope, compared to values of −22,209 and −22,437 for the model with the slope. We thus included the RV slope term in all of our models.

We rejected flat models (i.e., any instances where an expected transit was not found) in order to prevent the fit from running away, which can happen in the hotter chains when using parallel tempering. We required the number of independent draws to be greater than 1000 and determined that, with a Gelman–Rubin statistic (Gelman & Rubin 1992) of 1.0090 in the worst case, the chains were well mixed.

We initially allowed the radius of the 3.12 day planet to be unconstrained but found that grazing geometries were permitted, indicating that the light curve can set only a lower limit on the planet’s radius and an upper limit on its inclination. Similar to Rodriguez et al. (2018), we imposed a constraint on the radius of the 3.12 day planet based on the mass–radius relations by Chen & Kipping (2017). The impact is that this prior sets an upper limit on the planet radius (resulting from the measured planetary mass, informed by the RVs), while the lower limit on the planet radius is set from the observed depth of the transit. We emphasize that our data do not permit us to directly determine the radius of the 3.12 day planet. Although we state the value we determine by employing the Chen & Kipping (2017) prior, the planet radius could be much larger and should be determined by gathering data of greater precision, which would permit the determination of the four points of contact (if they exist). In Table 3, we have flagged all quantities that are affected by this prior.

In principle, if the radius from the Chen & Kipping (2017) relation were inconsistent with the lower limit from the transit, using this relation could bias the mass of the 3.12 day planet. To ensure that was not the case, we used ExoFASTv2 to run a two-planet fit of only the RV data. We found that the resulting RV semi-amplitude of LTT 1445Ac is in agreement with both that from our ExoFASTv2 global model fit with the radius constraint imposed, and the separate RV+GP fit we describe in Section 4.4.

Finally, we note that ExoFASTv2 rejects any samples where the planets’ projected orbits cross into each other’s Hill spheres, with the intention of constraining both planets’ eccentricity by rejecting unstable configurations. While this is a reasonable approximation, it is not a substitute for a detailed analysis of the long-term stability of the system, which is beyond the scope of this work.

4.3. Confirmation of the 3.12 Day Planet

Because our only detection of the transits of the 3.12 day planet is from the TESS light-curve data, in which the light from all three stars is blended together, the light curve itself does not prove that the planet orbits star A. Instead the proof
comes from our RVs of LTT 1445A. We first ran a global ExoFASTv2 fit using both sectors of TESS data and all of the RVs, accounting for only the confirmed 5.36 day planet. We added the RV jitter output from the global model in quadrature with the uncertainties on the RV residuals to properly weight the uncertainties from each instrument. We then created a Lomb–Scargle (L–S) periodogram using the L–S tool (VanderPlas & Ivezic 2015) in astropy (Astropy Collaboration et al. 2013, 2018), which we show in Figure 5. There is a peak at 3.12195 days with maximum L–S power at 0.298. The L–S False Alarm Probability (FAP) of a peak at this power is \(1.06 \times 10^{-5}\%\), indicating high significance of the signal and that indeed the 3.12 day planet also transits the primary star of LTT 1445.

We included the second planet in our global model to explore whether the addition of the second planet to our model would improve the fit to the data, under the assumption that it transits the primary star. The results indicate that the two-planet model is preferred over a single-planet model via the BIC and AIC metrics (BIC: \(-21,981\) versus \(-22,209\); AIC: \(-22,169\) versus \(-22,437\) for the one- and two-planet models, respectively). In Section 4.4, we conduct an independent analysis of the RV data using a GP to account for stellar activity, and similarly find that the two-planet model is strongly preferred.

We thus adopt the two-planet model as the most appropriate description of the data and list the median values of the fit parameters from our global ExoFASTv2 model for both planets in Table 3. We show the resulting transit and RV plots for each planet in Figures 6 and 7.

### 4.4. Radial-velocity Modeling with a Gaussian Process

Active regions on the surface of a rotating star may produce nonorbital RV signals due to both the magnetic suppression of the net convective blueshift of the photosphere, and through the effect of spots downweighting portions of the stellar velocity field on the visible hemisphere of the star (Meunier et al. 2010). The temporal evolution of these activity signals can be detrimental to the recovery of accurate planetary signals if not properly accounted for. Here we assess the impact of stellar activity in our RV data by explicitly treating stellar activity with a GP regression model component (e.g., Haywood et al. 2014; Rajpaul et al. 2015). Specifically, we model temporal correlations from rotationally modulated magnetic activity using a quasiperiodic GP following the methodology of Cloutier et al. (2017, 2020a, 2020b). To summarize, we adopt a separate quasiperiodic GP for each RV spectrograph due to their unique noise properties and the inherently chromatic nature of stellar activity. For each spectrograph indexed by \(s\), the quasiperiodic covariance kernel is

\[
k_{sij} = a_s^2 \exp \left[ -\frac{(t_i - t_j)^2}{2\lambda^2} - \Gamma^2 \sin^2 \left( \frac{\pi(t_i - t_j)}{P_{GP}} \right) \right],
\]

where \(a_s\) is the covariance amplitude for spectrograph \(s\), \(\lambda\) is the exponential timescale related to the lifetime of active regions, \(\Gamma\) is the coherence parameter, and \(P_{GP}\) is the periodic timescale related to the stellar rotation. We also fit an additive

\[
P_{GP} = \frac{P_{rot}}{2},
\]

where \(P_{rot}\) is the stellar rotation period. This approach allows for a flexible and physically motivated treatment of stellar activity effects in our RV data, enabling a more accurate recovery of planetary signals.

---

**Figure 5.** Lomb–Scargle periodogram of the residuals from the 5.36 day planet fit to the RV data of LTT 1445A. False alarm probabilities of 10%, 1% and \(1 \times 10^{-5}\%\) are noted (black dashed lines), as are the orbital periods for the 3.12 and 5.36 day period planets (dotted and solid orange and purple lines, respectively). A highly significant peak at 3.12 days is evident, which confirms that the 3.12 day planet also orbits LTT 1445A.

**Figure 6.** Transits of LTT 1445Ac (top) and LTT 1445Ab (bottom) observed with TESS. The data have been deblended to remove any signal from the stellar BC components and are shown in gray, while the orange and purple lines indicate the models for LTT 1445Ac and LTT 1445Ab.
RV orbital plots and residuals from the global ExoFASTv2 two-planet fit. In the top panel, we show the RV data folded at the 3.12 day period (and corrected for the 5.36 day planet, and the slope), with the model for the 3.12 day planet overlaid in gray; residuals to the fit of both planets are shown underneath, phase-folded to the 3.12 day planet period. Similarly, in the third panel, we show the RV data folded at the 5.36 day period (and corrected for the 3.12 day planet, and the slope), with the model for the 5.36 day planet overlaid in gray; residuals to the fit of both planets are shown underneath, phase-folded to the 5.36 day planet period. The data from ESPRESSO are plotted as orange squares, HARPS as blue circles, HIRES as pale red stars, MAROON-X as purple diamonds, and PFS as green triangles. The bottom panel illustrates the unphased RV data, where the gray curve indicates the combination of the 3.12 day and 5.36 day planet models and the linear slope due to the orbit of LTT 1445A about BC.

We proceed with modeling our full RV data set with a Keplerian model for each transiting planet, plus a GP activity model for each spectrograph. We use a custom-built python package, as described in Cloutier et al. (2021), to sample the joint posterior of our complete RV model that incorporates the affine-invariant MCMC sampler emcee (Foreman-Mackey et al. 2013) and the george package (Ambikasaran et al. 2015) to evaluate the marginalized likelihood of our GP activity model components. We adopt the model parameter priors reported in Table 2. We recover the median a posteriori GP hyperparameters and construct the predictive GP distributions for each spectrograph. We treat the mean function of each predictive distribution as the best-fit activity model for that spectrograph.

We use this analysis to evaluate the evidence for a second planet. Specifically, we calculate the Perrakis estimator (Perrakis et al. 2014), as used by Díaz et al. (2016), as an importance sampler to estimate the Bayesian model evidences for the one and two-planet RV+GP models. We find that the evidence ratio \( Z_{1}/Z_{2} = 1202 \), which supports the confirmation of the 3.12 day planet in our RV time series (Nelson et al. 2020). We conclude that a two-planet model is heavily favored over a one-planet model when including an explicit activity model in the form of a quasiperiodic GP.

### Table 2

**RV + GP Priors**

| Parameters | Prior |
|------------|-------|
| \( \log a_{i}/(\text{m s}^{-1}) \) | \( \mathcal{U}(−5, 5) \) |
| \( \log \lambda_{i}/(\text{days}) \) | \( \mathcal{U}(\log 1, \log 1000) \) |
| \( \log \Gamma \) | \( \mathcal{U}(–3, 3) \) |
| \( P_{\text{GP}} \) [days] | \( \mathcal{U}(85, 22) \) |

**LTT 1445ab RV Parameters**

| Parameter | Value |
|-----------|-------|
| \( P_{b} \) [days] | \( \mathcal{N}(3.123904, 0.000004) \) |
| \( T_{b0} \) [BJD] | \( \mathcal{U}(2458414.7815, 0.0004) \) |
| \( \log K_{b} / (\text{m s}^{-1}) \) | \( \mathcal{U}(−3, 3) \) |
| \( k_{b} = \sqrt{2} \cos \omega \) | \( \mathcal{U}(−1, 1) \) |
| \( k_{b} = \sqrt{2} \sin \omega \) | \( \mathcal{U}(−1, 1) \) |

**LTT 1445ac RV Parameters**

| Parameter | Value |
|-----------|-------|
| \( P_{c} \) [days] | \( \mathcal{N}(3.123904, 0.000004) \) |
| \( T_{c0} \) [BJD] | \( \mathcal{U}(2458414.7816, 0.0006) \) |
| \( \log K_{c} / (\text{m s}^{-1}) \) | \( \mathcal{U}(−3, 3) \) |
| \( k_{c} = \sqrt{2} \cos \omega \) | \( \mathcal{U}(−1, 1) \) |
| \( k_{c} = \sqrt{2} \sin \omega \) | \( \mathcal{U}(−1, 1) \) |

**Spectrograph Parameters**

| Parameter | Value |
|-----------|-------|
| \( \gamma_{i} / (\text{m s}^{-1}) \) | \( \mathcal{U}(−20, 20) + \text{median(rv)} \) |
| \( \log s_{i} / (\text{m s}^{-1}) \) | \( \mathcal{U}(−5, 5) \) |

4.5. Rotational Velocities and RVs of LTT 1445BC

We have determined with our MEarth photometry that the 1.4 day rotational modulation we see in the TESS data originates from LTT 1445BC, as discussed in Section 3.1.2. However, we are not able to determine from the photometric time series alone whether the B or C component is the source of that signal. Very-high-resolution spectra of LTT 1445BC might permit the measurement of the rotational velocities of each component, which would allow us to determine the source. We
noted in Section 3.3.2 that seven of our initial HARPS spectra of LTT 1445 were of the blended BC component. We downloaded these publicly available data and analyzed them using todocor (Zucker & Mazeh 1994) and the methods described in Winters et al. (2020) to extract individual RVs and rotational velocities ($v \sin i$) for the B and C components.

We used an observation of Barnard’s Star taken UT 2017 September 22 as the template for our analysis. We searched for the nonlinear least-squares maximum likelihood value for three parameters: the flux ratio $\alpha$ and the two values of $v \sin i$. We calculate $\alpha$, the ratio of the flux of C relative to that of B, to be 0.31 at wavelengths 6760–6836 Å (echelle aperture 71 of the HARPS data), roughly equivalent to $R_{KC}$. While this seems a bit low when compared to the $\alpha$ value of 0.50 we expect from photometry ($\Delta R_{KC} = 0.75 \pm 0.03$ mag; Henry et al. 2006), the angular separation between B and C at the time of these observations is comparable to the HARPS 1” fiber diameter. Thus, it is reasonable that there is less light from LTT 1445C landing in the fiber.

With this caveat in mind, we measure an average rotational broadening of 7.1 km s$^{-1}$ for LTT 1445C and 1.9 km s$^{-1}$ for LTT 1445B from the six spectra taken in September. These measurements suggest that the 1.4 day rotation period comes from the C component, and the 6.7 day marginal peak we see in the residual periodograms of the TESS and MEarth photometry in Figure 1 is probably the rotation period of the B component. (We note that these results are not completely conclusive, due to $\sin i$ degeneracy, to $v \sin i$ degeneracy.) Furthermore, we note that, while we have not robustly detected rotational broadening in B, our solutions do slightly prefer some.

As part of our analysis, we measure individual RVs for LTT 1445B and LTT 1445C of $-3.98 \pm 0.01$ km s$^{-1}$ and $0.24 \pm 0.20$ km s$^{-1}$. We use the least-squares deconvolution (Donati et al. 1997) to visualize the rotational broadening profiles of LTT 1445B and C in Figure 8.

Figure 8. Least-squares deconvolution profiles of LTT 1445B (green dashed line) and C (blue dashed line) from HARPS data (gray lines), which indicate the rotational broadening for each of the B and C components. The solid red line shows the joint fit of the broadened spectra.

4.6. Check of Consistency Across Fits

We performed a number of quality checks to ensure that our results are robust. We investigate three sets of parameters to check for consistency between model fits. We first compare the radius ratios we determine for each of the transit data sets. We then turn to the RV data, and compare both the RV semiamplitude and the eccentricities from different analyses.

We made separate adjustments to the PDCSAP light curves from both sectors of TESS data to correct the excess light from other stars in the optimal aperture. To ensure that we performed this correctly, we compare the results from fitting the transits of LTT 1445Ab from each sector of TESS data and find consistent planet-to-star radius ratios $R_p/R_*$. From the sector 4 data, we measure the radius ratio to be $0.0465 \pm 0.0015$, compared to that from sector 31, which is $0.0436^{+0.0015}_{-0.0014}$. We also compare the transit depth measurement results of LTT 1445Ab from our ground-based data to those from our global model. The measured radius ratio of the planet to the host star from ground-based data from MEarth and LCO are $0.0435 \pm 0.0021$ and $0.049^{+0.0004}_{-0.0013}$ (68.3% interval), respectively. These are both in agreement with the measured $R_p/R_*$ of $0.0451^{+0.0014}_{-0.0013}$ from our global model. The agreement between all three measurements...
of the radius ratio of LTT 1445Ab indicates that we correctly adjusted the TESS dilution factor. We are not able to perform a radius ratio comparison for LTT 1445Ac because we do not yet have an independent ground-based detection of it.

We compare the results from our global model to the results from our modeling of the RVs with a GP. The measured RV semi-amplitudes from the RV+GP model for planets c and b are 1.49 ± 0.17 m s⁻¹ and 2.28 ± 0.17 m s⁻¹, while they are 1.67 ± 0.20 m s⁻¹, and 2.60 ± 0.21 m s⁻¹ from our global model for planets c and b, respectively. All measurements are in agreement.

From the RV+GP model, the 95% confidence intervals for the eccentricities of the orbits of c and b are <0.165 and <0.089, respectively. These are in agreement with the results from our global model, which are <0.223 and <0.110, respectively.

Because the results from our RV+GP model and our global ExoFASTv2 model are in agreement, we determined that the inclusion of a GP to model any periodic stellar variability in our RVs is unnecessary. Thus, we adopt the median values from our global ExoFASTv2 model as our preferred results.

### 4.7. Search for Transit Timing Variations

Multiplanet systems sometimes exhibit transit timing variations (TTVs; Agol et al. 2005; Holman & Murray 2005), and we might expect them in the LTT 1445 system because the orbital periods of the two planets are not too dissimilar. Using the case of two planets not in resonance on circular orbits from Agol et al. (2005), we calculate that TTVs for the LTT 1445A planets are expected to be on the order of 1 min for each planet. We utilized ExoFASTv2’s TTV capability to search for variations in each planet’s transit midtimes, but did not detect any. We ran 213 chains for 3000 steps, thinned by 300, for a total number of 191.7 million simulations. For LTT 1445Ac, the shallow transit depth, grazing geometry, and low S/N of the light curves thwarted our efforts to reach a Gelman–Rubin value of less than 1.05 for the TTV parameters. Therefore, for this TTV analysis only, we adopt the criterion of convergence at a Gelman–Rubin value less than 1.1 (Gelman et al. 2004).

We omit transit 239 from our TTV analysis because it has two solutions, and provide the midtransit times for each planet’s transit from all of the time series photometry in Table 4. We show in Figure 9 that the transit midtimes of both planets are consistent with a linear solution when considering the uncertainties.

### 5. Discussion and Conclusions

We have measured the mass and radius of LTT 1445Ab to a precision of 9% and 5%, respectively. These precise mass and radius measurements permit the investigation of the planetary core mass fraction (CMF), which provides a probe for the planetary composition. Using the semi-empirical relation from Zeng et al. (2016), we calculate a CMF of 0.425 ± 0.283 for LTT 1445Ab. This is illustrated in the radius versus mass diagram in Figure 10, which includes composition curves from Zeng & Sasselov (2013). The planet falls squarely on the rocky compositional curve of 33% iron plus 67% magnesium silicate.

In the near future, we hope to determine the abundances of key elements in the stellar photosphere, and see if they match the ratios we have inferred for the planet for its bulk composition.

We have detected a second planet transiting LTT 1445A. The presence of additional planets orbiting LTT 1445A is not surprising, given the previously known existence of LTT 1445Ab (W19) and the recent result that 90.5 ± 2% of mid-M dwarfs host multiple planets less massive than 10 M⊕, and with orbital periods less than 50 days (Cloutier et al. 2021). LTT 1445A joins the growing list of mid-M dwarf systems in which additional planets have been revealed via follow-up observations of the original discovered planet. Some examples include GJ 357 cd (Luque et al. 2019), GJ 1132c (Bonfils et al. 2018), GJ 3473c (Kemmer et al. 2020), and LHS 1140c (Ment et al. 2019).

While we have measured the mass of LTT 1445Ac to a precision of 13%, the TESS data do not permit us to determine if all four points of contact are present in the transit curve of LTT 1445Ac, and hence whether the planetary transits are grazing. While the measured depth provides a minimum value for the radius of LTT 1445Ac, a grazing configuration allows acceptable solutions of arbitrarily large radii for the transiting object. If we impose a prior based on the mass–radius relation of Chen & Kipping (2017), then we find an acceptable, nongrazing fit to the light curve, and the resulting planet radius is 1.147 +0.055 −0.053 R⊕. This would correspond to a CMF of 0.235 ± 0.297, again consistent with the telluric value. Ultimately this question requires a more precise light curve, and we eagerly await the observations scheduled with HST (HST-GO-16503; PI: J. Winters).

Intriguingly, our results indicate that the two planets have circular (or low-eccentricity) orbits that are misaligned by at least −2.25 +0.28 −0.29 degrees (as inferred from the posterior of the global model fit). This value is a lower limit for several reasons.
### Table 3
ExoFASTv2 Median Values and 68% Confidence Intervals for LTT 1445Ac & LTT 1445Ab

| Parameter                   | Units | LTT 1445Ac | LTT 1445Ab |
|-----------------------------|-------|------------|------------|
| **Host Star Parameters:**   |       |            |            |
| $M_\star$                   | Stellar mass ($M_\odot$) | 0.257 ± 0.014 |          |
| $R_\star$                   | Stellar radius ($R_\odot$) | 0.265 ± 0.011 | 0.090 ± 0.010 |
| $T_{\text{eff}}$            | Stellar effective temp. (K) | 3340 ± 150 | 3340 ± 150 |
| [Fe/H]...                   | Stellar metallicity | -0.34 ± 0.09 | -0.34 ± 0.09 |
| $\gamma$...                 | RV slope ($\text{m s}^{-1} \text{day}^{-1}$) | -0.0081 ± 0.0026 | -0.0081 ± 0.0026 |
| **Planetary Parameters:**   |       |            |            |
| $P$...                      | Period (days) | 3.123903 ± 0.000034 | 3.587657 ± 0.000042 |
| $R_p$...                    | Radius ($R_\oplus$) | 1.147 ± 0.0015 | 1.035 ± 0.0066 |
| $M_p$...                    | Mass ($M_\oplus$) | 1.54 ± 0.19 | 2.87 ± 0.25 |
| $T_C$...                    | Time of conjunction** ($\text{BJD}_{\text{TDB}}$) | 2458412.58156 ± 0.00057 | 2458412.70851 ± 0.00049 |
| $T_R$...                    | Time of min. proj. sep.** ($\text{BJD}_{\text{TDB}}$) | 2458412.58156 ± 0.00057 | 2458412.70851 ± 0.00049 |
| $i$...                      | Inclination° (Degrees) | 87.43 ± 0.18 | 89.68 ± 0.22 |
| $e$...                      | Eccentricity°... | <0.223 | <0.110 |
| $K$...                      | RV semiamplitude (m s$^{-1}$)... | 1.67 ± 0.12 | 2.60 ± 0.21 |
| $\delta$...                 | Transit depth (fraction)... | 0.000157 ± 0.000015 | 0.00203 ± 0.00012 |
| $T_{\text{dur}}$...        | Total transit duration (days)... | 0.0201 ± 0.0011 | 0.05697 ± 0.00071 |
| $a$...                      | Semimajor axis (au)... | 0.02661 ± 0.00047 | 0.03813 ± 0.00068 |
| $R_p/R_\star$...            | Radius of planet in stellar radii°... | 0.0396 ± 0.0018 | 0.0451 ± 0.0013 |
| $a/R_\star$...              | Semimajor axis in stellar radii... | 21.56 ± 0.78 | 30.9 ± 11.1 |
| $b$...                      | Transit impact parameter... | 0.937 ± 0.012 | 0.17 ± 0.15 |
| $b_{\text{ES}}$...         | Eclipse impact parameter... | 0.977 ± 0.060 | 0.17 ± 0.12 |
| $p_p$...                    | Density° (g cm$^{-3}$)... | 5.57 ± 0.20 | 7.12 ± 1.1 |
| $\log(g_0)$...             | Surface gravity°... | 3.057 ± 0.042 | 3.217 ± 0.050 |
| $(F)$...                    | Incident flux ($10^9 \text{erg s}^{-1} \text{cm}^{-2}$)... | 0.0149 ± 0.0002 | 0.0073 ± 0.00013 |
| $T_{\text{eq}}$...         | Equilibrium temperature°(K)... | 508 ± 25 | 424 ± 21 |

| Wavelength Parameters:      |       |            |            |
| $u_1$...                    | Linear limb-darkening coeff... | 0.156 ± 0.070 | 0.156 ± 0.070 |
| $u_2$...                    | Quadratic limb-darkening coeff... | 0.396 ± 0.093 | 0.396 ± 0.093 |
| $A_{\text{Dil}}$...        | Dilution from neighboring stars... | -0.012 ± 0.048 | -0.012 ± 0.048 |

| Spectrograph Parameters:    | Relative RV Offset° (m s$^{-1}$) | RV Jitter (m s$^{-1}$) |
|-----------------------------|-----------------------------------|------------------------|
| ESPRESSO...                 | -5460.28 ± 0.50                  | 0.96 ± 0.17 |
| HARPS (2019)...             | -5458.7 ± 1.4                    | 1.9 ± 1.0 |
| HARPS (2020)...             | -5453.5 ± 0.63                   | 2.30 ± 0.45 |
| HIRES...                    | -1.75 ± 0.45                     | 2.29 ± 0.45 |
| MAROON-X (2019)...          | -0.14 ± 0.58                     | 1.16 ± 0.74 |
| MAROON-X (2020)...          | 1.84 ± 0.87                      | 0.93 ± 0.29 |
| PFS...                      | 0.41 ± 0.54                      | 1.87 ± 0.43 |

| TESS Transit Parameters:    | Added Variance $\sigma^2$ | Baseline flux $F_0$ |
|-----------------------------|----------------------------|---------------------|
| 2018...                     | 0.0000000317 ± 0.000000036 | 0.999995 ± 0.000031 |
| 2020...                     | -0.0000000097 ± 0.0000000036 | 1.000084 ± 0.000030 |

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

° Reference epoch = 2458686.217394.

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

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

° $a - 2 \sigma$ (95%) upper limits.

° Assumes no albedo and perfect redistribution.

The value for planet c was derived using the measured mass, the lower limit on the radius from the light curve, and Chen & Kipping (2017) exoplanet mass–radius relation to estimate the planetary radius.

First, it results from the inclusion of the mass–radius relation of Chen & Kipping (2017), which results in nongrazing transits. Grazing transits by a larger planet would result in an even larger misalignment. Second, even if this solution is correct and the transits are not grazing, we observe only a projection onto the line of sight of the true misalignment between the planetary orbits. Third, there is an (i, 180 – i) degeneracy and if the two orbits are on opposite sides of the central crossing, the mutual
We calculated the inclination would be $-2.91^{+0.34}_{-0.45}$ degrees, larger than the value presented above. For reference, the mutual inclination of the orbits of Venus and the Earth is 3.4 degrees.

We confirmed that the 1.4 day rotational modulation seen in the TESS data originates from LTT 1445BC. We have calculated the $v\sin i$ and RV values for LTT 1445B and C individually and find that the 1.4 day signal is likely the rotation period of LTT 1445C, while the less statistically significant 6.7 day signal may be the rotation period of LTT 1445B. From the activity and mass of LTT 1445A, we expect its rotation period to be $85 \pm 22$ days, based on the empirical relation in Newton et al. (2017). We have not yet detected the rotation period with MEarth, but our observations are ongoing. If our estimated rotation rates are correct, it implies that this triple star system is in a special evolutionary state, where A has spun down, B is in the process of spinning down, and C has not yet begun to spin down. LTT 1445 could be an important benchmark system for rotational evolution because it directly samples the mass dependence of the rapid spin-down phase discussed in the context of mid-to-late field M dwarfs by Newton et al. (2017). Intriguingly, the dynamical masses of the stars B and C can eventually be estimated directly, although this may take some time given the moderately long orbital period of $36.2 \pm 5.3$ yr (W19).

LTT 1445 is the second-closest known transiting exoplanet system, and the closest one with an M dwarf host star. Due to the efforts of MEarth (Nutzman & Charbonneau 2008; Irwin et al. 2015), TRAPPIST (Gillon et al. 2016, 2017), and TESS (Ricker et al. 2015), there are currently 10 systems among the M dwarfs within 15 pc with masses $\lesssim 0.35 M_{\odot}$ that are known to host transiting planets: GJ 1214b (Charbonneau et al. 2009), GJ 1132bc (Berta-Thompson et al. 2015; Bonfils et al. 2018), TRAPPIST-1 (Gillon et al. 2016, 2017; Grimm et al. 2018), LHS 1140bc (Dittmann et al. 2017; Ment et al. 2019), LHS 3844b (Vanderspek et al. 2019), LTT 1445Abc (W19; this work), L 98-59bcd (Kostov et al. 2019; Cloutier et al. 2019), GJ 357b (Luque et al. 2019), 2MA 0505-4756b (TOI-540b; Ment et al. 2021), and GJ 486b (Trifonov et al. 2021). Although challenging, these planets are among the very best available for near-future studies of their atmospheres. Kempton et al. (2018) provide empirical relations that allow for a quantitative comparison of the S/N of spectra acquired with the James Webb Space Telescope, based on the stellar and planetary properties. For LTT 1445Ab, we calculate a transmission spectroscopy metric (TSM) of 30 for LTT 1445Ab and an emission spectroscopy metric (ESM) of 5.7. If LTT 1445Ac is indeed terrestrial with the values listed in Table 3, then it would have an even higher TSM of 46 and an ESM of 8.7. For reference, Kempton et al. (2018) recommend minimum TSM and ESM values of 10 and 7.5, respectively, for planets that should be prioritized for future atmospheric studies. Furthermore, the proximity of LTT 1445A makes it a good candidate for stellar wind and mass-loss-rate measurements, as recently detailed in Wood et al. (2021), to determine their effect on the planetary atmospheres, should those be present.

W19 noted that, given the transit probability and number of nearby mid-to-late M dwarfs, TESS might find one more planet that is as accessible to follow-up study as LTT 1445Ab. LTT 1445Ac would appear to satisfy that criterion. As TESS has observed roughly 80% of the sky, the LTT 1445 system may remain the closest small star with transiting exoplanets. Then again, perhaps the remaining 20% of the sky will hold some as-yet undiscovered jewels.

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