Revisiting KELT-19Ab, WASP-156b, and WASP-121b in the TESS Era

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Abstract
We present a re-analysis of transit depths of KELT-19Ab, WASP-156b, and WASP-121b, including data from the Transiting Exoplanet Survey Satellite (TESS). The large ~21″ TESS pixels and point-spread function result in significant contamination of the stellar flux by nearby objects. We use Gaia data to fit for and remove this contribution, providing general-purpose software for this correction. We find all three sources have a larger inclination, compared to earlier work. For WASP-121b, we find significantly smaller values (13.7°) of the inclination when using the 30 minute cadence data compared to the 2 minute cadence data. Using simulations, we demonstrate that the radius ratio of exoplanet to star (Rp/R*) is biased small relative to data taken with a larger sampling interval although oversampling corrections mitigate the bias. This is particularly important for deriving subpercent transit differences between bands. We find the radius ratio of exoplanet to star (Rp/R*) in the TESS band is 7.5σ smaller than previous work for KELT-19Ab, but consistent to within ~2σ for WASP-156b and WASP-121b. The difference could be due to specific choices in the analysis, not necessarily due to the presence of atmospheric features. The result for KELT-19Ab possibly favors a haze-dominated atmosphere. We do not find evidence for the ~0.95 μm water feature contaminating transit depths in the TESS band for these stars but show that with photometric precision of 500 ppm and with a sampling of about 200 observations across the entire transit, this feature could be detectable in a more narrow z-band.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Exoplanet atmospheric composition (2021); Exoplanet systems (484); Exoplanet astronomy (486)

1. Introduction
Exoplanet transit depths in multiple bands in the light curve of a star provide clues to understanding the atmospheric composition of the exoplanet (Vidal-Madjar et al. 2003; Sing et al. 2011; Berta et al. 2012). The transmission spectrum leads to the detection of certain atomic and molecular species as well as haze and clouds in the planet atmosphere (Seager & Deming 2010). For instance, the transit spectrum of HD 209458b and XO-1b provides evidence for water and sodium absorption (Deming et al. 2013), while Sing et al. (2016) found evidence for water vapor in hot Jupiters. Similarly, WASP-12b has been characterized as a prototypical hot Jupiter with a high C/O ratio and significant presence of aerosols in its atmosphere (Madhusudhan et al. 2011; Sing et al. 2011). However, many of these analyses rely on Hubble Space Telescope spectroscopy. Hubble, due to its 90 minute orbit and passage through the vicinity of the Sun. It has four cameras with a total field of view of 24″ × 96″. The 50% ensquared-energy (within a square) half width is 1 detector pixel or 21″. The 90% ensquared-energy half width is 2 × 2 pixels. TESS produces multi-frame images at a cadence of 30 minutes with a baseline of at least 27 days and thus does not suffer from gaps in the light curve like Hubble. The photometric precision is about 1% sensitivity at 16th mag.

Here we present a re-analysis of the exoplanets KELT-19Ab, WASP-156b, and WASP-121b by combining TESS with other past observations. This paper is organized as follows. Section 2 describes the generation of TESS light curves, derivation of planet parameters from the TESS data using a Markov Chain Monte Carlo (MCMC) method, transit-parameter bias caused by binning, and a comparison between our values of inclination and Rp/R* with previous estimates. Constraints on the exoplanet atmosphere and the predictions of Rp/R* in the Kepler band and z-band, which is sensitive to water vapor, is presented in Section 3. In Section 4, we present a summary of our results.

2. Data Reduction
2.1. TESS Photometry
The exposure time of TESS for each frame is 2 s. Due to data downlink limitations, two image products are released; the individual frames in a few pixels around certain sources are integrated to 2 minute cadence, and are called target pixel files (TPFs). The frames are also integrated to 30 minute cadence for all the sources in the field of view to generate a full-frame...
of frames for KELT-19Ab, WASP-156b, and WASP-121b are 17612, 17612, and 15973, respectively. The median offsets for KELT-19Ab, WASP-156b, WASP-121b are 0.10, 0.27, and 0.07 in pixels. The standard deviations are 0.04, 0.09, and 0.04 in pixels. We apply the same astrometry correction when we analyze the 2 minute cadence image.

The TPF is an 11 pixels × 11 pixels cutout of the image around the TESS Input Catalog (TIC). The pipeline versions are spoc-3.3.57-20190215 for KELT-19Ab, spoc-3.3.51-20181221 for WASP-156b, and spoc-3.3.57-20190215 for WASP-121b.

We measured the photometry of the host star in a circular aperture with TPF. The aperture radius was chosen to be 3 pixels, corresponding to 63″. The flux from pixels whose fractional area falls within the aperture is correctly accounted for. The sky background per image was estimated as the median of the pixels that constitute the lowest fifth percentile in flux and subtracted from the photometry in the aperture. The standard deviation of these pixels yields the background noise in the photometry. The quadrature sum of this noise and the Poisson noise of the source itself is the photometric uncertainty of the data point. The contribution to the photometry from nearby unresolved stars was then removed based on the relationship between the flux-brightness profile and the distance to the Gaia centroid of the unresolved stars (details in the next section).

2.2. Correction for Blending Sources

We then corrected the photometry to remove contamination from the surrounding unresolved sources. We used external information from the Gaia database (Gaia Collaboration et al. 2016, 2018), including position and brightness in Gaia G and Rp bands. The Gaia Rp band is similar to the bandpass of TESS. However, it is less sensitive than the Gaia G band. For stars that have Rp band photometry from Gaia, we used its brightness information directly. For faint stars with no Gaia Rp band detection, we used their G-band flux density and applied a median color correction which is the median flux-density ratio between the Rp band and G band of stars in the vicinity.

In order to estimate the flux from these contaminating sources inside the aperture centered on the exoplanet host star, we used the TESS FFI data to derive the relationship between flux contamination and the distance between the center of the photometric aperture and a source. We chose 5 bright (brighter than 13 mag in Gaia G band) and isolated sources from the TIC. It is difficult to guarantee complete isolation to within 6 TESS pixels but the bright stars were chosen to have no detectable companions in the image and the Gaia catalog showed an absence of sources within 5 mag of the bright stars. We divided the 6 pixel radius circle into a set of annuli, each of 0.25 pixel width. We then chose a set of positions that traverse the annulus circumference in 0.1 pixel steps. With each of these positions as center, we performed aperture photometry by measuring the flux density within a circular aperture of radius 3 pixels as for the exoplanet host star. Sky subtraction was performed as described in the previous section. The maximum separation between the center of the aperture and from the bright star position was allowed to be 6 pixels where the contamination is negligible. This is because TESS has a 90% ensquared energy within a half width of 2 pixels.

Finally, we normalized the set of sky-subtracted flux-density measurements by the flux measured at zero separation. We
repeated this for 5 targets and for each target we used 10 frames. The median and standard deviation of the normalized brightness profile for all these measurements is shown in Figure 2.

The relationship between distance and brightness profile was then estimated by the polynomial fitting of the data pairs (see in Figure 2). We then apply this relation to every contaminating source whose brightness has been estimated as described above to derive the flux density contributed by the blending source to the photometry of the exoplanet host star. This contaminating flux density, which is constant for a particular exoplanet host star, was then removed from our photometry values.5 The total contaminating flux percentage and uncertainty for the three stars is 6.22% ± 0.42%, 0.64% ± 0.03%, and 31.49% ± 1.79% for KELT-19Ab, WASP-156b, and WASP-121b, respectively.

In addition, there is a possibility of blending from an unresolved binary companion. In the case of WASP-156b and WASP-121b, there is no evidence of a binary companion in past work (Delrez et al. 2016; Demangeon et al. 2018). In the case of KELT-19Ab, a nearby stellar companion was detected with the Palomar/Hale 200” telescope using the near-infrared adaptive optics (AO) system (Siverd et al. 2018). The stars have a measured magnitude difference of ΔJ = 2.50 ± 0.06 and ΔKs = 2.045 ± 0.03. Siverd et al. (2018) report a flux ratio of 0.0270 ± 0.0034 at a wavelength of 5200 ± 150 Å, effective temperatures of 7500 ± 200 K for the primary component, and 5200 ± 100 K for the secondary component. We search the ATLAS library (Kurucz 1993) grid based on the flux ratio and effective temperatures. The best-fit stellar templates are multiplied by the TESS filter response to estimate the brightness of the companion star and its contamination to the TESS photometry. The derived contaminating flux fraction is 0.059 ± 0.006 which we remove.

2.3. Detrending of the Light Curve and Comparison with TESS-PDC Light Curve

Measuring an accurate transit depth of an exoplanet requires a high-precision light curve. This requires detrending to remove the long-term trends in the photometry outside of transit events (Gibson et al. 2012; Smith et al. 2012; Vanderburg &

5 The code to apply this correction is available at https://github.com/sailovy/TESS_Deblending/.

Figure 2. The normalized brightness profile of stars as seen by TESS used to estimate the amount of contamination of an exoplanet host stars’ photometry by background stars seen by Gaia. The scatter points are the observed data. The red line indicates the polynomial fit to the data.

Figure 3. Fits to the TESS TPF transit light curves of KELT-19Ab (top), WASP-156b (middle), and WASP-121b (bottom). The blue points are observed, 2 minute data decontaminated using Gaia photometry. The green points are bins of 30 minute cadence data. The red dashed line represents the best-fit transit model to the 2 minute data. The yellow region shows the 1σ confidence region of the fits. The midpoint of the transit event is shifted to half the period, at the center of the x-axis. The free parameters in the fits are inclination, semimajor axis, and limb-darkening parameters as shown in Figure 4.

Johnson 2014; Aigrain et al. 2015). Since we already know the existence of an exoplanet around these stars, we can use prior knowledge of the transit midpoint time, period, and transit duration to perform a simple detrending. To do this, we predicted the transit time in the TESS light curve and extracted the parts of the light curve spanning 0.6 day centered at the transit midpoint.

The data points of the light curve during the planetary transit were first masked out. We fitted a linear function to the signal in the masked, cutoff, light curve. The fit is used to estimate and remove the trending in the light curve within a day. We applied this correction for every data point of the extracted light curve and fold the light curve around the transit midpoint to get the transit events shown in Figure 3. We also tried higher-order polynomial functions, including orders of 2, 3, 5, and 10. The difference in the detrended light curve is negligible for these choices of polynomials.
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Table 1

Planetary Parameters

| Parameters | Description | KELT-19Ab 68\% Confidence | WASP-156b 68\% Confidence | WASP-121b 68\% Confidence |
|------------|-------------|-----------------------------|-----------------------------|-----------------------------|
| $R_p/R_*$  | Planet/star radius ratio in TESS | 0.09576 ± 0.00082 | 0.0670 ± 0.0012 | 0.1234 ± 0.0004 |
| $i$ [deg]  | Inclination | 88.7 ± 0.7 | 90.1 ± 1.4 | 89.9 ± 1.6 |
| $a/R_*$    | Semimajor axis of planet orbit in units of stellar radii | 9.04 ± 0.19 | 12.98 ± 0.73 | 3.81 ± 0.03 |
| std of residual | Parts per million | 1253 | 2130 | 1763 |
| Reduced $\chi^2$ | Reduced chi-square | 1.001 | 1.0009 | 1.0004 |

Fitting Results with Fixed Inclination and Semimajor Axis

| Parameters | Description | KELT-19Ab 68\% Confidence | WASP-156b 68\% Confidence | WASP-121b 68\% Confidence |
|------------|-------------|-----------------------------|-----------------------------|-----------------------------|
| $R_p/R_*$  | Planet/star radius ratio in TESS | 0.09940 ± 0.00048 | 0.0662 ± 0.0009 | 0.1230 ± 0.00025 |
| Planet/star radius ratio in other works | | 0.10713 ± 0.00092 (a) | 0.0685 ± 0.0002 (e) | 0.1220 ± 0.0002 (b), (c), (d) |
| Difference significance | Difference between TESS and former work in $\sigma$ | 7.549 | 1.533 | 1.789 |
| $i$ [deg]  | Inclination | 85.41_{-0.31}^{+0.34} (a) | 89.1_{-0.6}^{+0.5} (d) | 87.6 ± 0.6 (b), (c) |
| $a/R_*$    | Semimajor axis of planet orbit in unit of stellar radii | 7.50_{-0.20}^{+0.28} (a) | 12.8_{-0.3}^{+0.4} (e) | 3.754_{-0.021}^{+0.023} (b), (c) |
| std of residual | Parts per million | 1266 | 2132 | 1765 |
| Reduced $\chi^2$ | Reduced chi-square | 1.021 | 1.001 | 1.002 |
| linLimb    | Linear limb-darkening coefficient | 0.29 ± 0.04 | 0.37 ± 0.04 | 0.24 ± 0.03 |
| quadLimb   | Quadratic limb-darkening coefficient | 0.23 ± 0.04 | 0.23 ± 0.04 | 0.21 ± 0.04 |

References. (a) Siverd et al. (2018); (b) Delrez et al. (2016); (c) Evans et al. (2017); (d) Evans et al. (2018); (e) Demangeon et al. (2018).

The photometric data reduction could be influenced by factors already corrected in our pipeline or by some factors beyond the consideration of our work, e.g., point-spread function variation, focus changes, bad pixels, and thermal variations. In order to make sure these factors do not dominate the precision of transit depth measurements, we compare our results with light curves derived using the TESS presearch data conditioning (PDC) modules. The PDC light curve is produced by the TESS collaboration considering the factors above. The comparison covers three targets in this work as well as HD-219666, an isolated exoplanet host star identified by TESS, which is bright compared to its surrounding stars (Esposito et al. 2019). The debiasing correction for HD-219666 is ± 0.006%.

We compare the median flux of our light curve with the $G$-band flux reported by Gaia (Gaia Collaboration et al. 2018). The flux-density ratio of our decontaminated flux to Gaia flux for KELT-19Ab, WASP-156b, WASP-121b, and HD-219666 is 97, 71, 90, and 80, respectively (in arbitrary units). The standard deviation is 9.7. The flux ratio of PDC flux to Gaia flux is 95, 66, 86, 75, respectively. The standard deviation is 11.0. This indicates that the two techniques are perfectly consistent with each other. Furthermore, we find that the derived planetary transit depths from the two sets of light curves of these sources are within 1$\sigma$ of each other.

2.4. Planet Parameters Derived from TESS-detected Transits

2.4.1. Fitting with Free Inclination and Semimajor Axis

We used an MCMC fitting technique to derive the parameters of the exoplanets from the TESS transit curves (Mandel & Agol 2002). We adopted a circular orbit as in previous articles that confirmed the corresponding exoplanets with orbital periods derived therein (Delrez et al. 2016; Demangeon et al. 2018; Siverd et al. 2018). The value of $T_{\text{eff}}$, log $g$, and [Fe/H] was taken from the discovery articles as well. The free parameters in our fit are the radius ratio of the planet to the host star ($R_p/R_*$), the inclination of the planet’s orbit ($i$), the semimajor axis in units of stellar radii ($a/R_*$), time offset of transit center ($T_0$), and the limb-darkening parameters ($a_1$ for a linear limb-darkening coefficient, $a_2$ for a quadratic limb-darkening coefficient), as shown in Table 1. Except for limb darkening, the other parameters have uniform priors. We adopted the common inclination prior of $\pm 0.51$ for a quadratic limb-darkening model is applied. The priors for the limb-darkening coefficients are $0.36 \pm 0.05$ and $0.22 \pm 0.05$ for linLimb and quadLimb, respectively.

In the case of KELT-19Ab, we adopted $T_{\text{eff}}$, log $g$, and [Fe/H] of $7500 \pm 110$ K, $4.127 \pm 0.029$ cgs, $0.12 \pm 0.51$. As in Siverd et al. (2018), a quadratic limb-darkening model is applied. The priors for the limb-darkening coefficient are $0.27 \pm 0.05$, $0.23 \pm 0.05$, for the linear (linLimb) and quadratic coefficients (quadLimb), respectively.

In the case of WASP-156b, the $T_{\text{eff}}$, log $g$, and [Fe/H] values are 5871 \pm 57 K, 4.35 \pm 0.03 cgs, 0.10 \pm 0.10. A quadratic limb-darkening model is used (Demangeon et al. 2018). The priors for limb-darkening coefficients are $0.36 \pm 0.05$ and $0.22 \pm 0.05$ for linLimb and quadLimb, respectively.

In the case of WASP-121b, the $T_{\text{eff}}$, log $g$, and [Fe/H] values are 6460 \pm 140 K, 4.2 \pm 0.2 cgs, and 0.13 \pm 0.09. The limb-darkening model used is the quadratic limb-darkening model.
For each fitting, the parameters’ probability distributions are derived using the Python MCMC tool, PYMC (Patil et al. 2010). We apply 200,000 iterations for the whole chain, and ignore the first 100,000 steps to ensure the chain is stable. The best-fitting light curves are shown in Figure 3, respectively. The distribution of $R_p/R_*$, $a/R_*$, inclination and limb-darkening parameters are shown in Figure 4. The best-fit results are shown in Table 1.

The inclinations derived from TESS TPF data for KELT-19Ab, WASP-156b, and WASP-121b are $3.3\pm1.0$, $1.0\pm0.8$, and $2.63\pm1.0$, respectively. The TESS radius ratio for WASP-121b is $0.05\pm0.05$ larger than the results based on identification paper, respectively. Specifically, in case of WASP-121b, the inclination derived is more consistent with the follow-up work value of 89.1 by Evans et al. (2018). Due to TESS’s continuous sampling with 2 minute and high-precision photometry, the ingress and egress of transit are well monitored. These short phases in the transit duration are extremely sensitive to the inclination and semimajor axis. We, therefore believe that the TESS result as well as the result from Evans et al. (2018) on the inclination for WASP-121b are robust.

2.4.2. Fitting with Fixed Inclination and Semimajor Axis

Although our best fits are similar to those of other work, there are clear signs of differences, particularly in our derived inclination and transit depths. In order to focus on differences in the radius ratio caused by wavelength-dependent properties, we refit the TESS light curves by fixing the inclination and semimajor axis to the referenced work (Evans et al. 2017; Demangeon et al. 2018; Siverd et al. 2018).

The fitting followed the same procedure as Section 2.4.1. The fitting results, as well as the derived parameters from previous work, are listed in Table 1. The differences between our fits and the result from the former work are shown in Figure 5. The reduced chi-square in the fits is slightly larger than in the best fit from the previous section (Table 1). The small difference in the chi-square values indicates that the value of inclination and semimajor axis preferred in other work is reasonably consistent with the TESS data but is not the preferred solution.

The fixed parameter MCMC fits have reduced uncertainties due to the strong priors on inclination and semimajor axis. These constraints on inclination and semimajor axis disturb the Gaussian distribution of other parameters. The revision for the $3\sigma$ rules for the parameters is beyond this work (see Pukelsheim 1994; MacKay 2002; Hogg & Foreman-Mackey 2018). We cited the $1\sigma$ uncertainty from the MCMC derived standard deviation for each parameter.

Our fits to the TESS data give us a consistent planet-to-star radius ratio for WASP-121b and WASP-156b at the $\sim2\sigma$ level (Table 1). However, the planet-to-star radius ratio for KELT-19Ab is $7.5\sigma$ smaller than in previous work (Siverd et al. 2018). The TESS radius ratio for WASP-121b is deeper than the median value including all the bands with the TESS wavelength range from Evans et al. (2018). For WASP-156b, the radius ratio is smaller than that of past work (Demangeon et al. 2018).

2.5. Transit-parameter Bias Caused by Binning

Sampling cadence results in morphological distortions to the transit light curve due to sampling of transit ingress and egress (Kipping 2010). For the TESS cadence, an assessment of the

(Delrez et al. 2016; Evans et al. 2018). The limb-darkening coefficients that we applied to our MCMC fits are $0.33\pm0.05$ and $0.21\pm0.05$, respectively.
parameter bias is necessary for assessing the differences in transit depths for different bands.

We first investigate if our derived parameters from the TESS 2 minute data are consistent with those from the 30 minute data by repeating the whole data reduction and fitting with the 30 minute cadence image. In the case of free inclination fitting, the inclinations derived for KELT-19Ab, WASP-156b, and WASP-121b are 4°6.6, 5°1.1, and 13°6.6 smaller than the results based on 2 minute binning data, respectively. Furthermore, the residuals from the light curve for WASP-121b when fixing the inclination shows obvious structure during the phase of ingress and egress (seen in Figure 6). The radius ratio when fixing inclination and semimajor axis is 0.1195 ± 0.0004, about 7σ smaller than the 2 minute result, with substantially worse chi-square values. The inconsistency, especially for WASP-121b, motivates a simulation for a more detailed assessment of the differences.

We simulated 1000 light curves for each source. The input parameters were set to that in the discovery papers (Table 1; Delrez et al. 2016; Demangeon et al. 2018; Siverd et al. 2018). We note that for WASP-121b, the newest reported inclination is 1°5 larger than initially assessed (Evans et al. 2018). The result from Evans et al. (2018) is also well matched to the TESS TPF-derived result as shown in Table 1, but for the purpose of the simulations, we chose the value from the discovery paper. The time sampling for the simulated light curve is 1 s and is binned to 2 and 30 minutes. The numbers of transit events is set to be the same as the event numbers observed by TESS. We add a Gaussian error to the light curves. The adopted 1σ scatter is the standard deviation of the residuals from fitting the TESS light curves scaled by a factor of the square root of the timescale. These simulated light curves are then fit as described earlier.

Figures 7 and 8 show the distribution of derived parameters compared to the input values. We find that the magnitude of bias in the derived parameters, especially inclination and semimajor axis, depends on the duration time of the transit, especially ingress and egress. We take WASP-121b as an illustrative example that gives the largest inclination difference. The derived median inclination value with the 30 minute cadence data is 76.4 deg with a standard deviation of 0°6.7, 11°2 smaller than the input value. The inclination decrease is because the binning smooths the rapid change of the flux decrease during ingress and egress. The planet-to-star radius ratio when fixing the inclination and semimajor axis is 0.1201 ± 0.00035, also smaller than the input value at the level of ∼ 5σ (seen in Figure 7).

Kipping (2010) provides a numerical solution to compensate for biases caused by binning, using Kepler’s equations. We
investigate the derived correction through a simulation in which 1000 simulated light curves of 30 minutes cadence are generated with input parameters the same as described before. Using the batman routine (Kreidberg 2015), we resample and integrate the simulated light curves to 2 minute cadence. The derived fit inclination is 86.4 ± 1.3 deg, indicating that resampling corrects the inclination bias to within 1σ. However, the derived \( R_p/R_\star \) from the resampled light curve has a median and scatter of 0.1231 ± 0.00068. The bias in \( R_p/R_\star \) is 0.0011 ± 0.000068, while the bias without resampling is −0.0019 ± 0.00035.

Such differences of ~0.8% are negligible for most transit applications but need to be considered carefully for atmospheric characterization. We use further simulations to assess if any \( R_p/R_\star \) bias after oversampling still exists. The resampling cadence is changed from 1 to 10 minutes with a step of 1 minute. The resampling cadence below 1 minute is also tested from 10 to 50 s with a step of 10 s. The \( R_p/R_\star \) reveals an offset at the level of 0.001 with an uncertainty ~0.0006 when the resampling cadence is below 5 minutes. The offset is larger and increases with resampling cadence when the resampling cadence is larger than 5 minutes.

In addition, we apply simulations to check if the bias still exists when the initial sampling rate is 2 minutes. The resampling cadence is set to be 30 s, 1 minute, and 2 minutes. The derived \( R_p/R_\star \) does not reveal any evidence of offset, suggesting that the batman routine itself does not induce any systematic bias. We thus conclude that the resampling technique (Kipping 2010; Kreidberg 2015) significantly reduces the systematic bias caused by undersampling. However, we conclude that the very high precision (\( R_p/R_\star \sim 0.5\% \)) needed for atmospheric analysis needs careful correction for sampling-induced systematics.

In the case of light curves with 2 minute sampling, the bias is assessed in the same way. The best-fit inclination for WASP-121b is found to be 87.7 ± 1.3 deg. The planet-to-star radius ratio with a fixed inclination and semimajor axis is 0.1219 ± 0.0004. We find the difference between the derived values and the input values to be negligible with the 2 minute data.

For all three sources, we find that the simulations with 2 minute sampling yield parameters similar to the input value. Meanwhile, with 30 minute cadence, the result is significantly biased when we do not correct for undersampling (Kipping 2010; Kreidberg 2015). Also, the differences in the inclination and planet-to-star radius ratio between 2 and 30 minute cadence matches the difference between them from real TESS data. From these simulations, we therefore conclude that the biases in parameters from fitting TESS data of different cadence comes from binning and that the fit parameters from the 2 minute cadence data for our three targets are robust.

Finally, we undertake a simulation to investigate the dependence of inclination and semimajor axis upon sampling time interval when not applying the oversampling technique (Figure 8). The sampling time interval in the simulation ranges from 1 to 50 minutes. For each interval, the light curve is generated as described above and fit. We duplicate 10 simulations for each sampling interval. The median fit values and standard deviations of the derived parameters are shown in Figure 8 for each sampling interval. It is clear that the inclination and semimajor axis are not significantly biased when the sampling time is less than 5 minutes. Also, the result indicates that the inclination and semimajor axis derived are distorted to be smaller when applying a larger sampling interval (as shown in Figure 8). This suggests that great care must be taken when comparing transit depths in different bands, especially when the light-curve sampling intervals are likely to be quite different. The simulations were conducted without the oversampling correction (Kipping 2010) which can mitigate the bias of inclination and semimajor axis as previously discussed.
2.6. A Difference in Stellar Activity Level?
As explained in Pont et al. (2008) and Agol et al. (2010), differences in the number of star spots between past observations and the TESS observations could account for differences in the measured transit depth. It was estimated that when the flux density of the star changes by 1% because of stellar spots, the influence on the radius ratio is of the order of $10^{-2} R_p/R_*$, comparable to the uncertainty of our TESS-derived value. None of the three sources studied in this paper (Evans et al. 2017; Demangeon et al. 2018; Siverd et al. 2018) have shown any past evidence of stellar activity. Furthermore, if star spots were significant, the standard deviation of the light curve outside the transit should be different from that during transit. So we conclude that the impact of star spots on our transit depth measurement is negligible.

3. Atmospheric Constraints
Our primary scientific motivation for undertaking this work was to compare $R_p/R_*$ in the TESS band with the value from previous work to constrain the atmospheres of the exoplanets. In particular, the TESS bandpass is significantly redder than the Kepler band and encompasses the 0.95 $\mu$m water feature. The presence of these features in the planets’ atmospheres would result in a larger value of $R_p/R_*$ in the TESS band. For instance, the $R_p/R_*$ of KELT-19Ab in TESS data is significantly smaller, at the level of 7.5$\sigma$, indicating the possible existence of atmospheric features.

Our fixed inclination fits (Table 1) allow for a more direct comparison with past work. The significance level of differences in $R_p/R_*$ are 7.5, 1.5, and 1.8$\sigma$ for KELT-19Ab, WASP-156b, and WASP-121b, respectively. We discuss the implications of this difference for each of the exoplanets.

3.1. KELT-19Ab
KELT-19Ab is a giant planet transiting a moderately bright ($V \sim 9.9$ mag) A8V star with an orbital period of 4.61 days (Siverd et al. 2018). The host star has $M_*=1.62^{+0.25}_{-0.27} M_\odot$, $R_*=1.83 \pm 0.09 R_\odot$. The planet has a radius of $R_p=1.91 \pm 0.11 R_\oplus$.

The ground-based light curves from Siverd et al. (2018) in each band ($B$, $g$, $r$, $i$ (7519 Å), $I$ (8317 Å) and $z$ (8992 Å)) were obtained. They are refit to compare the variation in $R_p/R_*$ values between the different bands to that presented for the combined band. The light curves are performed with binary component deblending and linear detrending, using the same method as described previously. The flux contamination fraction adopted is the same as Siverd et al. (2018). The ground-based light curve does not have a long and stable baseline like the TESS data. The long-term trend is therefore very difficult to estimate and dominates the $R_p/R_*$ uncertainty.

We masked the transit phase in the light curve as described previously and fit the baseline using different baseline lengths. This is repeated 5 times with the baseline length reduced by a factor of 10% each time. Three detrended light curves with the best residual are used for transit fitting. The $R_p/R_*$ and uncertainty are taken as the median value and the standard deviation of three fitted values. We do not fit the $B$- and $r$-band data because of the short baseline and partial coverage of the transit. The $i$-band values from the different telescopes are combined. KELT-19Ab has $R_p/R_*$ of 0.10713 derived from a joint fit to ground-based ($B$, $g$, $r$, $i$, $I$, $z$) data. The refit of our result presents smaller values of $R_p/R_*$ in each band compared to what has previously been published (0.10713, Siverd et al. 2018). This indicates the $R_p/R_*$ differences might partially come from a different process choice.

We fitted the multiband transit data with the grid of atmospheric transmission spectra from Goyal et al. (2018, 2019) which are developed for hot, H_2/He-dominated Jupiters. This model is a 1D radiative–convective–equilibrium solution based on the ATMO code (Tremblin et al. 2015, 2016; Drummond et al. 2016). ATMO solves the radiative transfer for isothermal pressure–temperature (P–T) profiles with opacity and chemical abundance being other parameters. The grid model has a parameter space of two chemical scenarios, 22 temperatures, 4 planetary gravities, 5 atmospheric metallicities, 4 C/O ratios, 4 scattering haze, 4 cloud parameters, and a scaling factor to the specific planetary radius. Modifying specific chemical abundance will lead to different chemical equilibrium which is avoided in the use of the forward-grid model.

In order to fit the model, we minimized the chi-square value between the observations and model predictions at all the bands. The model prediction at each band is derived by the following equation where $S_\lambda$ is the filter response.

$$
\frac{R_p}{R_*} = \frac{\int R_p S_\lambda d\lambda}{\int S_\lambda d\lambda}.
$$

We find that the haze-dominated model at 1500 K has the least $\chi^2$ of 2.80 (Figure 9). A clear model showing weak water vapor with rainout condensation at 1500 K gives the second best $\chi^2$ of 3.05, while a clear model showing strong water vapor at 1000 K has the third best $\chi^2$ of 3.26. A flat, opaque, featureless model is also shown with a $\chi^2=3.14$. Other models resulted in much larger chi-square values (more than 6) and are not consistent with the data. We also obtain the Bayesian information criterion (BIC) for evaluating the model evidence. BIC theory is effective when the data points are much more than the free parameters (Liddle 2007). This might not be the case for KELT-19Ab but we still present the BIC here for reference. The BIC is 4.41, 9.49, 9.69 for haze, weak-water, and strong-water models. The BIC is 4.74 for an opaque featureless model. The free parameter numbers of the opaque featureless model, haze, weak-water, and strong-water models are 1, 1, 4, and 4, respectively. The smaller $\chi^2$ and BIC of the haze model suggest that it is possibly the best interpretation given the current data. However, given the relatively narrow range in $\chi^2$ values and small difference in BIC, the opaque featureless model would also be a reasonable explanation.

Based on our fits, we predicted the possible $R_p/R_*$ value in the Kepler band and $z$-band based on these templates (Figure 9). The Kepler band would show $R_p/R_*$ of 0.1003 for a haze-dominated atmosphere and 0.0997 for a clear model. In the $z$-band, the presence of water would introduce a significant difference in the ratio. We estimate that a clear atmosphere model with strong-water contribution would show $R_p/R_*=0.1002$. The value is smaller, 0.0990, from a clear model with faint water, as well as from a haze-dominant model.

We find that a difference of 1.2% in $R_p/R_*$ arises between strong-water contribution and faint-water contribution models. If we scale from our TESS measurements and assume that the signal-to-noise ratio depends on the square root of the number of points in the transit, we find that with 500 ppm precision for
200 data points around the transit event in the \( z \)-band, one can distinguish between these two scenarios. This is, of course, a minimum since additional systematic effects can affect the measurements.

Alternately, instead of using our derived values of \( R_p/R_* \) in each of the optical bands, we can use the value of Siverd et al. (2018) which is derived from a joint fit to all the bands. We treated their joint value of \( R_p/R_* \) as the value in each band. The uncertainty follows the equation: \( \sigma_{\text{joint}} = \sigma_i / \sqrt{N} \), according to the error-propagation law. \( \sigma_{\text{joint}} \) is the joint-band uncertainty, \( N \) is the number of bandpasses, \( \sigma_i \) is the uncertainty in the band \( i \). We assume the uncertainty in each band is the same.

Fitting \( R_p/R_* \), the \( \chi^2 \) values for the different atmospheric models discussed—haze, strong-water, weak-water, and opaque featureless model—are 47.52, 50.68, 53.24, and 55.07, respectively. The BIC is 49.47, 58.46, 61.02, and 57.02 for the same models, respectively. Other models resulted in much larger chi-square values (more than 60) and are also not consistent with the data. Again, we find that a haze-dominant atmosphere is preferred, as before.

We followed the same procedure as for KELT-19Ab to analyze the differences in \( R_p/R_* \) in different bands. The published value of \( R_p/R_* \) for comparison with our TESS analysis, is taken from Demangeon et al. (2018) at Johnson \( R \), Gunn \( r \), Johnson \( I \), and Gunn \( z \) (Figure 10).

We find that a clear atmosphere at 1500 K with strong-water contribution (best-fit model) has a \( \chi^2 \) of 2.35 and a BIC of 8.80. The faint-water model at the same temperature follows with a worse \( \chi^2 \) of \( \sim 2.44 \) and a BIC of 8.87. The haze model has a \( \chi^2 \) of 2.44 and a BIC of 4.04. An opaque featureless model has the same \( \chi^2 \) of 2.35 as the best-fit model. The smallest BIC value of 3.96 indicates that the data might prefer the opaque featureless atmosphere model. The strong-water contribution causes a shift of 0.9% in the \( z \)-band prediction of \( R_p/R_* \) compared to the faint-water model. In the Kepler band, the haze-dominant model has a larger \( R_p/R_* \) of 1.3% than the no-atmosphere model. We conclude that the current measurements are consistent with an opaque featureless model.

### 3.3. WASP-121b

WASP-121b was discovered by Delrez et al. (2016). It is a hot Jupiter around a main-sequence star (\( V = 10.4 \) mag, \( 1.353_{-0.079}^{+0.080} M_\odot, 1.458 \pm 0.030 R_\odot \)) with a period of 1.28 days. The planet has a mass of \( 1.183_{-0.062}^{+0.064} M_\oplus \) and a radius of \( 1.865 \pm 0.044 R_\oplus \).

We used external observations from Delrez et al. (2016) and Evans et al. (2016, 2018) in conjunction with our analysis of the TESS data (Figure 11). These measurements utilized the...
Figure 10. $R_p/R_*$ of WASP-156b in different bandpasses. The top panel shows the clear model with strong water (blue solid line), the haze-dominant model (green solid line), and the opaque featureless model (brown solid line). The red point is $R_p/R_*$ derived from TESS. The black points are $R_p/R_*$ from former work with the blue diamonds the “clear model” predictions at those bands. The yellow diamond is the model prediction at the SDSS $z$-band, the green diamond is the model prediction at the Kepler band. In the bottom panel, a clear model with strong water (green solid line) is shown along with a faint-water model (orange solid line) for comparison. The empty green diamond is a strong-water model prediction at the Kepler band. The dark green diamond is the strong-water model prediction at the SDSS $z$-band. The brown diamond is the faint-water model prediction at the $z$-band.

Figure 11. The transmission spectrum for WASP-121b. The solid yellow point is the best-fit value of $R_p/R_*$ from the TESS light curve. However, if the inclination is fixed to previous work for a consistent comparison, the solid red point is $R_p/R_*$ derived from TESS data. The black points are $R_p/R_*$ from former measurements. The gray solid line is the best fit from Evans et al. (2018). The blue line shows the haze model. The brown line shows the opaque featureless model. The black line indicates a clear atmosphere at a cool temperature (shifted for clarity).
standard ground-based filter, STIS, and WFC3 instruments on Hubble and span 0.3–1.65 μm. As outlined in Evans et al. (2018), a global fit for the whole spectrum is challenging due to the complex problem of nonequilibrium chemistry.

Our fits with the inclination fixed to past work, however, yield a value of $R_p/R_*$ which is in very good agreement with that of Evans et al. (2018). The median value of the radius ratio is 0.1225 at the wavelength range of TESS. To fit the spectrum, we again use the general grid model from Goyal et al. (2019).

The best-fit model from Evans et al. (2018) is still the best-fit model when we add the TESS constraints. The fitting has a reduced chi-square of 4.91, a BIC of 449.74, with 492 data points, 4 fixed, and 4 free parameters (in Figure 11). The fixed parameters are local condensation, atmospheric metallicities at 20 ×, haze parameters of 1.0, and no cloud. The fitted free parameters are a temperature of 1500 K, gravity at 10 m s$^{-2}$, C/O ratio of 0.7, and planet radius (without atmosphere). An opaque featureless model has a reduced chi-square of 5.19 and a BIC of 477.39. The haze-dominant model has a chi-square of 5.87 and a BIC of 538.76. A transmission model at 1500 K with features of potassium, sodium, and water vapor has a much larger reduced chi-square of 27.40, a BIC of 543.44, and seems to be ruled out. According to BIC theory, any model having a BIC smaller than 10 is favored (Kass & Raftery 1995).

4. Summary and Discussion

We have analyzed the TESS data for KELT-19Ab, WASP-156b, WASP-121b to measure $R_p/R_*$ in a broadband spanning 600–1000 nm. We identify the significant role of contamination by unresolved background stars in the TESS data and use Gaia data to subtract their contribution to the transit light curves. We provide general-purpose software to address this issue for all TESS data. We determine the light curves through a linear fit to the photometry near the transit events. To derive the exoplanet transit parameters, we performed two ways of MCMC model fitting: with and without inclination and semimajor axis fixed. The former in particular helps with the comparison with past work on these stars. Using simulations, we demonstrate the systematic biases in inclination and radius ratio with 30 minute cadence data when no correction for undersampling is undertaken (Kipping 2010). We also find the inclination and semimajor axis are distorted to be smaller with larger sampling times. However, we find that 2 minute sampling does not cause any bias for transit parameters. The atmosphere of these three exoplanets was then constrained based on $R_p/R_*$ in different bands.

In the case of KELT-19Ab, we find that the TESS-measured $R_p/R_*$ is $\sim 7.5 \sigma$ smaller than past work. The $R_p/R_*$ could be due to the choice of analysis or due to the presence of atmospheric features which further observations in narrower bands can reveal. The model fitting possibly favors a haze-dominant atmosphere. In the case of WASP-156b, we find that the TESS transit depths agree with previous work and prefer a no-atmosphere model fit to the measurements. In the case of WASP-121b, the fits to the TESS light curve prefer the newest reported inclination. We find that the atmospheric transmission spectrum is best fitted with a 1500 K model with water vapor as reported before.

Our work shows that exoplanet atmospheric model constraints benefit from high-precision continuous photometry which provides strong constraints on key parameters such as inclination. Adding one high-precision observation at certain bands improves the constraints on atmospheric composition. Since TESS has now observed the Northern Hemisphere, we have Kepler (Borucki et al. 2010) and TESS constraints on a few bright stars, which will help assess the role of haze in exoplanet atmospheres. Finally, we show that precision photometry with $\sim 500–1000$ ppm in the $\nu$-band can help directly constrain the presence of water vapor in the exoplanet atmosphere when combined with precise TESS photometry.

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