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Refined Orbital and Physical Parameters of the Hot Jupiter Qatar-1b from TASTE and TESS Photometry

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ABSTRACT

We present a refined analysis of the orbital and physical parameters of the hot Jupiter Qatar-1b, leveraging high-precision photometric data from the Transiting Exoplanet Survey Satellite (TESS) and the ground-based TASTE (Asiago Search for Transit Timing variations of Exoplanets) survey. The TESS dataset comprises observations from Sectors 24, 25, and 42, providing multiple transits with a 2-minute cadence. The TASTE data were acquired using the 1.82-meter Galileo Telescope in Asiago, Italy, during a single transit event on November 6, 2021. We performed a detailed reduction of the TASTE data, including bias and flat-field corrections, and extracted the light curve using aperture photometry with careful selection of comparison stars and aperture size, achieving a photometric precision of approximately 1%. For the TESS data, we utilized the Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP) fluxes, and we further refined the light curves by applying the `wotan` package to mitigate residual systematic trends using a biweight filter with a window length of 1.0 day. A transit mask was employed during the detrending process to preserve the transit signal. We modeled the transit light curves using the `batman` package, adopting a quadratic limb-darkening law. The limb-darkening coefficients were estimated using the `ldtk` toolkit, providing priors for the TASTE analysis and freely fitting those coefficients for the TESS analysis. We employed an affine-invariant Markov Chain Monte Carlo (MCMC) ensemble sampler, implemented in the `emcee` package, to derive the posterior distributions of the model parameters. Our analysis yields a refined planet-to-star radius ratio of $R_p/R_* = 0.1549 \pm 0.0024$ from the TESS data and consistent values of $R_p/R_* = 0.154^{+0.010}_{-0.009}$ and $R_p/R_* = 0.156^{+0.012}_{-0.010}$ from the TASTE data using two different reference stars. We also derived refined values for the orbital period ($P = 1.42003 \pm 0.00001$ days), mid-transit time, impact parameter, and scaled semi-major axis. The derived parameters are consistent with, but more precise than, previously published values. Our results showcase the power of combining high-precision space-based photometry from TESS with targeted ground-based follow-up observations from facilities like TASTE to improve our understanding of exoplanetary systems.

Key words. planetary systems - exoplanets - techniques: photometric - stars: individual: Qatar-1

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1. Introduction

The study of transiting exoplanets has revolutionized our understanding of planetary systems. The transit method, which relies on the detection of the periodic dimming of starlight as a planet passes in front of its host star, allows for the determination of fundamental planetary properties, such as the planet's radius, orbital period, and inclination (e.g., **??**). The combination of transit photometry with other techniques, such as radial velocity measurements, enables the determination of the planet's mass, density, and bulk composition (e.g., **?**).

Qatar-1b is a hot Jupiter orbiting a K-type dwarf star (V = 12.84 mag; **?**). The planet was discovered by the Qatar Exoplanet Survey, which utilized wide-field robotic telescopes to monitor hundreds of thousands of stars, searching for transit signals. The discovery paper reported an orbital period of approximately 1.42 days, a planet-to-star radius ratio of $R_p/R_* = 0.1161 \pm 0.0027$, and an impact parameter of $b = 0.46^{+0.09}_{-0.12}$. Subsequent studies have refined these parameters and provided further characterization of the system (e.g., **??**).

In this work, we present a new photometric analysis of Qatar-1b using data from the Transiting Exoplanet Survey Satellite (TESS; **?**) and the Asiago Search for Transit Timing Variation of Exoplanets (TASTE) project. TESS is a NASA space mission designed to perform an all-sky survey to search for transiting exoplanets around bright, nearby stars. Its high-precision photometry, with a typical precision of a few hundred parts per million (ppm), allows for the detection and characterization of small planets and the detailed study of transit light curves. The TASTE project utilizes the 1.82-meter Galileo Telescope at the Asiago Astrophysical Observatory to obtain high-precision, ground-based light curves of transiting exoplanets, with the primary goal of searching for transit timing variations (TTVs) that could reveal the presence of additional bodies in the system (**?**).

Our main objective is to leverage the complementary strengths of the TESS and TASTE datasets to obtain improved estimates of the orbital and physical parameters of Qatar-1b. Specifically, we aim to refine the planet-to-star radius ratio (R_p/R_*), which is a crucial parameter for understanding the planet's internal structure and composition. The high precision of the TESS data, combined with the independent measurements from TASTE, allows for a robust determination of this parameter. We also investigate the system's limb-darkening properties, which can provide insights into the host star's atmospheric structure.

The paper is organized as follows: in Section 2, we describe the TESS and TASTE observations and data products. Section 3 outlines the data reduction procedures for both datasets, including bias and flat-field corrections, aperture photometry, and detrending of the light curves. In Section 4, we detail the transit modeling, the treatment of limb darkening, and the Markov Chain Monte Carlo (MCMC) analysis. Section 5 presents the results of our analysis, including the derived system parameters and comparisons with previous studies. Finally, Section 6 summarizes our findings and discusses their implications.

2. Observations

2.1. TASTE Observations

The TASTE dataset for Qatar-1 analyzed in this work was obtained on the night of November 6, 2021 (BJD 2459525), using the 1.82-meter Galileo Telescope at the Asiago Astrophysical Observatory, operated by the University of Padova. The telescope is located at Mount Ekar (latitude: 45°50'50" N, longitude: 11°34'08" E) at an elevation of 1366 meters above sea level. The observations were performed using the Asiago Faint Object Spectrograph and Camera (AFOSC) instrument, equipped with an ANDOR iKon-L CCD detector. The CCD has a 2048×2048 array of 13.5 μm pixels, providing a field of view of approximately 13.4 x 13.4 arcminutes with the focal reducer in place.

The observations were carried out in the Sloan r' filter using a 2x2 binning mode, resulting in a plate scale of 0.52 arcseconds per pixel. The exposure time for the science frames was set to 20 seconds. A total of 725 science frames were collected, covering a full transit of Qatar-1b, along with pre- and post-transit baseline. In addition to the science frames, 30 bias frames and 30 sky flat-field frames were obtained for calibration purposes. The bias frames were taken with 0-second exposures at the beginning and end of the night, while the flat-field frames were acquired during evening twilight using the same filter and binning as the science observations.

The seeing during the observations, estimated from the FWHM of the target star in the reduced images (using a Moffat function), varied between approximately 5.5 and 8.5 pixels, with a median value of approximately 6.3 pixels. The airmass ranged from 1.04 at the beginning of the observations to a minimum of 1.01, and then increased to 1.67 by the end of the night.

2.2. TESS Observations

The TESS observations of Qatar-1 analyzed in this study consist of short-cadence (2-minute) photometry obtained in Sectors 24 and 25. The dates of the observations for each sector are:

- Sector 24: April 22, 2020 - May 19, 2020 (BJD 2458961 - 2458988)
- Sector 25: May 19, 2020 - June 13, 2020 (BJD 2458988 - 2459014)

The TESS mission utilizes four wide-field cameras, each with a field of view of 24 x 24 degrees, to monitor the brightness of stars across a large fraction of the sky. The cameras are equipped with red-sensitive CCD detectors, providing a wide bandpass that extends from approximately 600 to 1000 nm.

The TESS data were obtained from the Mikulski Archive for Space Telescopes (MAST) portal. We used the Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP) fluxes, which have been corrected for instrumental systematic effects and crowding. We selected only data points with a quality flag of zero, indicating good data quality. The TESS observations provide a total of 4 (?) transits of Qatar-1b. The number of transits was identified using the `wotan` package. The typical photometric precision for the PDCSAP fluxes of Qatar-1 in the used sectors is approximately 250 ppm (?) per 2-minute cadence.

Table 1: Comparison between the values obtained for the errors on a single bias frame and on the master bias

STD of a single frame	=	7.752045 [e]
READOUT NOISE	=	7.100000 [e]
Expected STD for the median bias	=	1.415323 [e]
STD of the median bias	=	1.769451 [e]

3. Data Reduction

3.1. TASTE Data Reduction

The reduction of the TASTE data was performed using standard procedures for bias and flat-field correction, followed by aperture photometry.

A master bias frame was created by taking the median of 30 individual bias frames, after converting the raw data from ADUs to electrons using the gain factor of 1.91 e/ADU. The uncertainty of the master bias was estimated by measuring the standard deviation of pixel values within a selected region (from column 300 to 350) of the master bias frame, yielding a value of 1.77 e. This value is slightly higher than the expected standard deviation of the median, which is calculated as the standard deviation of a single bias frame (7.75 e, obtained from header's statistics) divided by the square root of the number of bias frames ($\sqrt{30}$), resulting in 1.42 e.

A master flat frame was constructed by first subtracting the master bias from each of the 30 flat-field frames and then normalizing each frame by its median value within a selected region (central 50x50 pixels box). The normalized frames were then combined using a median to create the master flat. The uncertainty of the master flat was estimated by propagating the uncertainties of the individual flat-field frames, taking into account the readout noise, the master bias error, and the Poisson noise of the flat-field signal. The master flat was saved as a pickle file named median_normalized_flat.p.

The 725 science frames were corrected by subtracting the master bias and dividing by the master flat. The uncertainty for each corrected science frame was calculated using standard error propagation:

$$\sigma_{S_b} = \sqrt{\sigma_{RON}^2 + \sigma_{MB}^2 + S_b}, \tag{1}$$

$$\sigma_{S_{bf}} = S_{bf} \sqrt{\left(\frac{\sigma_{S_b}}{S_b}\right)^2 + \left(\frac{\sigma_{MF}}{MF}\right)^2}, \tag{2}$$

where σ_{S_b} is the uncertainty of the bias-subtracted frame, σ_{RON} is the readout noise (7.4 e), σ_{MB} is the uncertainty of the master bias, S_b is the bias-subtracted frame, $\sigma_{S_{bf}}$ is the uncertainty of the bias- and flat-field-corrected frame, S_{bf} is the corrected frame, σ_{MF} is the uncertainty of the master flat, and MF is the master flat.

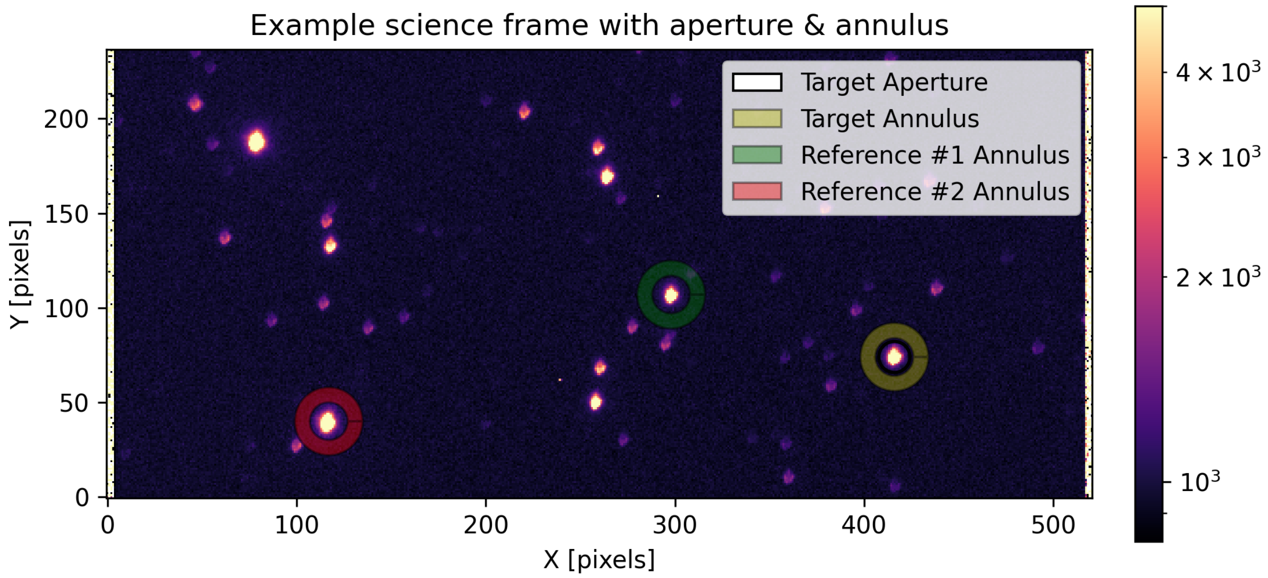

Fig. 1: A bias- and flat-field-corrected image highlighting the target star in yellow and two comparison stars in red and green, labeled **Ref #1** and **Ref #2**. Each star is accompanied by an annulus for sky measurements, both with the target and reference stars' annuli extending from 10 (inner radius) to 18 (outer radius) pixels.

Precise timestamps for each science frame were obtained by adding half of the exposure time (10 seconds) to the recorded Julian Date (JD). A barycentric correction was then applied using the `astropy.time` package to convert the timestamps to Barycentric Julian Date in the Barycentric Dynamical Time standard (BJD_TDB). The average difference between JD_UTC and BJD_TDB was approximately -66.95 seconds. The light travel time to the solar system barycenter was also computed, with an average value of approximately 4.84 minutes.

Aperture photometry was performed on the corrected science frames using the `photutils` package. The target star (Qatar-1) and two comparison stars of similar brightness, labeled as Ref #1 and Ref #2, were identified in each frame (see Figure 1). The centroids of the stars were determined using an iterative 2D Gaussian fit. The function refines the centroid position by iteratively calculating the weighted average of the pixel coordinates within a circular region around the initial guess, with the weights given by the pixel values. The iteration stops when the change in centroid position is less than 0.1% between consecutive iterations. An annulus with an inner radius of 13 pixels and an outer radius of 18 pixels was used to estimate the sky background around each star (see Figure 1).

The aperture radius for the photometry was chosen to be 8 pixels, based on the analysis of the curve of growth (see Figure 2). This radius ensures that at least 95% of the star's flux is enclosed within the aperture. The sky-subtracted flux for each star was calculated by summing the pixel values within the aperture and subtracting the median sky background per pixel, multiplied by the number of pixels in the aperture.

The uncertainty in the aperture flux was estimated using the following equations:

$$\sigma_{\rm Sky} = \frac{\sqrt{\sum_1^{N_{\rm pixel}} \sigma^2_{S_{bf,n}}}}{N_{\rm pixel}}, \tag{3}$$

$$\sigma_{AF} = \sqrt{\sum_1^{N_{\rm pixel}} \left(\sigma^2_{S_{bf,n}} + \sigma^2_{\rm Sky}\right)}, \tag{4}$$

where $\sigma_{\rm Sky}$ is the uncertainty of the sky background per pixel, $N_{\rm pixel}$ is the number of pixels in the aperture, $\sigma_{S_{bf,n}}$ is the uncertainty of each pixel in the corrected science frame, and σ_{AF} is the uncertainty of the aperture flux.

Differential photometry was performed by dividing the aperture flux of the target star by the aperture flux of each comparison star. This resulted in two light curves, one for each comparison star. The out-of-transit standard deviations of the two light curves were 0.010630 and 0.010210 for Ref #1 and Ref #2, respectively. Both light curves were used in the subsequent transit modeling.

3.2. TESS Data Reduction

The TESS data reduction started with the PDCSAP fluxes from the short-cadence (2-minute) observations. We applied a stringent quality flag filter, retaining only data points with a quality flag of zero, indicating no detected anomalies.

To remove residual systematic trends in the TESS light curves, we used the `wotan` package (**?**). We tested both the `biweight` and `hspline` detrending methods with different window lengths. The `biweight` method with a window length of 1.0 day provided the best results, yielding the lowest out-of-transit standard deviation of the flattened light curve (0.005033 using a transit mask, see section 10 of the Python code). The transit events were masked during the detrending process to prevent

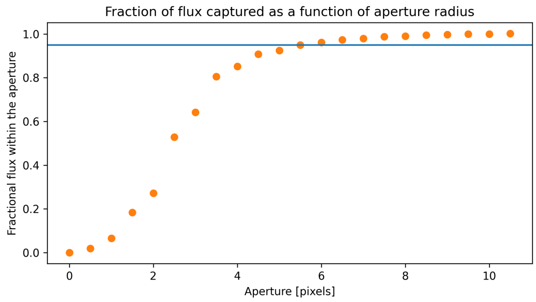

Fig. 2: Total star flux inside an increasing aperture radius. The measured flux was divided by the total flux inside the largest aperture, to obtain a normalized value. The horizontal line identifies the 95% of the total flux inside the largest aperture. To measure the aperture photometry flux of each star we selected a radius of 5 pixels, the radius in which at least 95% of the total flux is included in the aperture.

them from influencing the trend fitting, using the transit time and period derived from the initial `batman` fit. The transit mask was defined with a duration of 2.982 hours, approximately twice the transit duration reported by **?**. The PDCSAP fluxes were divided by the best-fitting trend to obtain flattened light curves. The uncertainties were adjusted by dividing them by the same trend values.

We used the period and the transit time obtained from the preliminary `batman` fit and we identified individual transit events in the TESS light curves (see Figure **??**).

4. Data Analysis

4.1. Transit Model

We employed the `batman` package (**?**) to model the transit light curves of Qatar-1b. The model utilizes the analytical transit equations of **?** and is parameterized by the following orbital and physical parameters: the orbital period (P), the time of inferior conjunction (T_0), the planet-to-star radius ratio (R_p/R_*), the scaled semi-major axis (a/R_*), the orbital inclination (i), the eccentricity (e), and the argument of periastron (ω). For our analysis, we assumed a circular orbit ($e = 0$) and fixed the argument of periastron to $\omega = 90°$.

4.2. Limb Darkening Treatment

We adopted a quadratic limb-darkening law, as defined by **?**:

$$\frac{I(\mu)}{I_0} = 1 - u_1(1-\mu) - u_2(1-\mu)^2, \tag{5}$$

where $I(\mu)$ is the specific intensity at an angle θ from the normal to the stellar surface, I_0 is the intensity at the center of the disk, $\mu = \cos(\theta)$, and u_1 and u_2 are the quadratic limb-darkening coefficients. We used the reparameterization proposed by **?**:

$$q_1 \equiv (u_1 + u_2)^2, \quad q_2 \equiv \frac{u_1}{2(u_1 + u_2)}, \tag{6}$$

which has been shown to improve sampling efficiency in MCMC analyses.

To obtain reliable limb-darkening coefficients, we employed the `ldtk` package (**??**). We used the PHOENIX stellar atmosphere models and adopted the following stellar parameters for Qatar-1, based on the values reported by **?**: effective temperature $T_{\rm eff} = 4910 \pm 100$ K, surface gravity $\log g = 4.55 \pm 0.10$, and metallicity [Fe/H] = 0.20 ± 0.10. We generated limb-darkening profiles for the Sloan r' filter (used for TASTE observations) and the TESS filter, using the ‘SVOFilter‘ function in `ldtk` with the corresponding shortcuts ‘SLOAN/SDSS.r‘ and ‘TESS‘, respectively.

We created limb darkening profiles using 2000 samples and resampled them with a linear-z method using 100 samples, inflating the uncertainties by a factor of 10. We then computed the quadratic limb darkening coefficients in the q_1, q_2 formalism, performing a Monte Carlo sampling with 10000 samples. The resulting coefficients and their uncertainties are:

- TESS: $q_1 = 0.37 \pm 0.07$, $q_2 = 0.32 \pm 0.16$ (corresponding to $u_1 = 0.51 \pm 0.10$, $u_2 = 0.10 \pm 0.10$)
- TASTE (Sloan r'): $q_1 = 0.56 \pm 0.08$, $q_2 = 0.07 \pm 0.10$ (corresponding to $u_1 = 0.65 \pm 0.10$, $u_2 = 0.08 \pm 0.10$ for Ref #1 and $u_1 = 0.66 \pm 0.10$, $u_2 = 0.07 \pm 0.09$ for Ref #2)

For the TESS light curve fitting, we allowed the limb-darkening coefficients to float freely, with uniform priors between 0.0 and 1.0. For the TASTE light curve fitting, we adopted Gaussian priors based on the `ldtk`-derived values.

4.3. MCMC Analysis

We employed the affine-invariant ensemble sampler `emcee` (**?**) to explore the parameter space and obtain posterior distributions for the model parameters. We initialized 50 walkers near an initial guess, the latter is reported in section 9.2 of the Python code, and let them evolve for 20,000 steps. The first 2,500 steps were discarded as burn-in to ensure convergence to the stationary distribution, and the chains were thinned by a factor of 100 to reduce autocorrelation between samples.

The convergence of the MCMC chains was assessed using the Gelman-Rubin statistic (**?**), which compares the variance within each chain to the variance between chains. We required that the Gelman-Rubin statistic be less than 1.01 for all parameters, indicating good convergence. Visual inspection of the trace plots was also performed to ensure that the chains were well-mixed and had converged to a stable distribution.

The posterior distributions were used to derive the median values and uncertainties for each parameter. The uncertainties were estimated as the 16th and 84th percentiles of the marginalized posterior distributions, corresponding to 1σ confidence intervals for Gaussian distributions.

4.4. Model Parameters and Priors

Our model consists of 14 parameters:

1. T_0: Time of inferior conjunction (BJD_TDB)
2. P: Orbital period (days)
3. R_p/R_*: Planet-to-star radius ratio
4. a/R_*: Scaled semi-major axis
5. i: Orbital inclination (degrees)
6. q_1 (TESS): Quadratic limb-darkening coefficient (TESS)
7. q_2 (TESS): Quadratic limb-darkening coefficient (TESS)
8. q_1 (TASTE): Quadratic limb-darkening coefficient (TASTE)
9. q_2 (TASTE): Quadratic limb-darkening coefficient (TASTE)

10. c_0: Constant term of the polynomial trend (TASTE)
11. c_1: Linear term of the polynomial trend (TASTE)
12. c_2: Quadratic term of the polynomial trend (TASTE)
13. $\sigma_{\rm TESS}$: Jitter term for TESS data, added in quadrature to the photometric uncertainties
14. $\sigma_{\rm TASTE}$: Jitter term for TASTE data, added in quadrature to the photometric uncertainties

We adopted uniform priors for most parameters, with boundaries defined based on physical considerations and initial estimates from **?** and our preliminary `batman` fits. The boundaries for each parameter are listed below:

- P: [$\mathrm{P_{initial}} - 0.5$, $\mathrm{P_{initial}} + 0.5$] days, where $\mathrm{P_{initial}} = 1.42003$ days
- T_0: [$T_{0,\rm initial} - 0.5$, $T_{0,\rm initial} + 0.5$] days, where $T_{0,\rm initial}$ is the initial guess for each dataset (TESS or TASTE)
- R_p/R_*: [0.0, 0.5]
- a/R_*: [0.0, 20.0]
- i: [0.0, 90.0] degrees
- q_1 (TESS): [0.0, 1.0]
- q_2 (TESS): [0.0, 1.0]
- q_1 (TASTE): [0.0, 1.0]
- q_2 (TASTE): [0.0, 1.0]
- c_0: [0.0, 1.0]
- c_1: [-1.0, 1.0]
- c_2: [-1.0, 1.0]
- $\sigma_{\rm TESS}$: [0.0, 0.05]
- $\sigma_{\rm TASTE}$: [0.0, 0.05]

Gaussian priors were used for the stellar density and the TASTE limb darkening parameters. For the stellar density, we adopted a value of $\rho_* = 1.44 \pm 0.19\,\rho_\odot$, based on the values from **?** and our analysis. For the TASTE limb darkening coefficients, we used the values obtained from the `PyLDTk` analysis (Section 4.2).

4.5. Log-Likelihood Function

The log-likelihood function is given by:

$$\ln \mathcal{L} = -\frac{1}{2} \sum_{i=1}^{N} \left[\frac{(f_i^{\rm obs} - f_i^{\rm model})^2}{\sigma_i^2} + \ln(2\pi\sigma_i^2) \right], \tag{7}$$

where $f_i^{\rm obs}$ and $f_i^{\rm model}$ are the observed and modeled fluxes for the i-th data point, σ_i is the uncertainty of the i-th data point (including the jitter term), and N is the total number of data points.

For the TESS data, the model flux is computed using `batman` with the appropriate limb-darkening coefficients. For the TASTE data, the model flux is multiplied by a second-order polynomial to account for any residual trends:

$$f_{\rm TASTE}^{\rm model} = f_{\rm transit}^{\rm model} \times (c_0 + c_1\Delta t + c_2\Delta t^2), \tag{8}$$

where $\Delta t = t - t_{\rm med}$, and $t_{\rm med}$ is the median of the TASTE time stamps.

The jitter terms, $\sigma_{\rm TESS}$ and $\sigma_{\rm TASTE}$, are added in quadrature to the photometric uncertainties:

$$\sigma_{i,\rm TESS}^2 = \sigma_{i,\rm phot,TESS}^2 + \sigma_{\rm TESS}^2, \tag{9}$$

$$\sigma_{i,\rm TASTE}^2 = \sigma_{i,\rm phot,TASTE}^2 + \sigma_{\rm TASTE}^2, \tag{10}$$

where $\sigma_{i,\rm phot,TESS}$ and $\sigma_{i,\rm phot,TASTE}$ are the photometric uncertainties for the TESS and TASTE data, respectively.

4.6. Light Curve Fitting

We performed independent fits to the TESS and TASTE light curves. For the TESS data, we fitted all available transits simultaneously. The transit epoch and period were constrained using the values derived from the `wotan` analysis, with Gaussian priors centered on the `wotan` values and standard deviations of 0.00034 days and 0.00001 days, respectively. The planet-to-star radius ratio, scaled semi-major axis, and inclination were allowed to float freely, with uniform priors as specified in Section 4.4.

For the TASTE data, we fitted each light curve (obtained with a different reference star) separately. The orbital period was fixed to the value derived from the TESS data analysis (1.42003 days). The transit epoch was constrained using the values derived from the TESS analysis, with Gaussian priors centered on the fitted TESS values and standard deviations of 0.00059 days for the first reference star, and 0.00061 days for the second reference star. The planet-to-star radius ratio, scaled semi-major axis, and inclination were allowed to float freely, with uniform priors. A second-order polynomial was included in the model to account for any residual trends in the out-of-transit data, with uniform priors for the coefficients.

The log-probability function, which combines the log-likelihood and the log-prior, was evaluated at each step of the MCMC sampling. The `emcee` sampler was used to generate posterior distributions for all model parameters.

5. Results

The MCMC analysis yielded well-constrained posterior distributions for the model parameters. The results are summarized in Table 2, where we report the median values and the 16th and 84th percentiles (corresponding to 1σ uncertainties) for each parameter. Corner plots showing the correlations between the parameters are presented in Figure **??**. The plots for TASTE data have been obtained using `PyGTC` package (**??**), while the plot for TESS data have been obtained using `corner` package (**?**).

The TESS light curve analysis resulted in a planet-to-star radius ratio of $R_p/R_* = 0.1549 \pm 0.0024$. The orbital period and transit epoch were determined to be $P = 1.42003 \pm 0.00001$ days and $T_0 = 2459445.54724^{+0.00035}_{-0.00034}$ (BJD - 2450000), respectively. The scaled semi-major axis was $a/R_* = 6.24 \pm 0.33$ and the impact parameter was found to be $b = 0.649^{+0.044}_{-0.051}$. The fitted limb-darkening coefficients for the TESS bandpass were $q_1 = 0.37 \pm 0.07$ and $q_2 = 0.32 \pm 0.16$. The TESS jitter term was estimated to be $\sigma_{\rm TESS} = 0.00002^{+0.00002}_{-0.00001}$.

The TASTE light curves, analyzed independently using two different reference stars, yielded consistent results. For reference star #1, we obtained $R_p/R_* = 0.154^{+0.010}_{-0.009}$, $a/R_* = 6.2 \pm 0.7$, $b = 0.64^{+0.11}_{-0.17}$, and $T_0 = 2459525.40245^{+0.00059}_{-0.00058}$ (BJD - 2450000). For reference star #2, we found $R_p/R_* = 0.156^{+0.012}_{-0.010}$, $a/R_* = 6.3 \pm 0.8$, $b = 0.69^{+0.12}_{-0.26}$, and $T_0 = 2459525.4021^{+0.00061}_{-0.00060}$ (BJD - 2450000). The fitted limb-darkening coefficients for the TASTE r'-band were $q_1 = 0.56 \pm 0.08$, $q_2 = 0.07 \pm 0.10$ for reference star #1, and $q_1 = 0.56 \pm 0.08$, $q_2 = 0.07 \pm 0.09$ for reference star #2, consistent with the values derived from `PyLDTk`. The polynomial coefficients for the TASTE light curves were found to be $c_0 = 0.2448 \pm 0.0016$, $c_1 = 0.026 \pm 0.025$, $c_2 = -0.042 \pm 0.068$ for reference star #1, and $c_0 = 0.2174 \pm 0.0016$, $c_1 = 0.031 \pm 0.025$, $c_2 = -0.064 \pm 0.068$ for reference star #2. The TASTE jitter terms were estimated to be $\sigma_{\rm TASTE} = 0.00543^{+0.00050}_{-0.00043}$ for Ref #1 and $\sigma_{\rm TASTE} = 0.00556^{+0.00052}_{-0.00044}$ for Ref #2.

Table 2: Parameters obtained from the light curve fitting and comparison with values from **?**.

Statistics on the model parameters obtained from the posterior samples				
	TESS	TASTE with Ref #1	TASTE with Ref #2	**?**
P [days]	1.42003 ± 0.00001	1.42002 ± 0.00006	1.42002 ± 0.00006	1.4200233 ± 0.0000039
T_c [BJD-2450000]	$9445.54724^{+0.00035}_{-0.00034}$	$9525.40245^{+0.00059}_{-0.00058}$	$9525.4021^{+0.00061}_{-0.00060}$	5852.10326 ± 0.00041
R_p/R_*	0.1549 ± 0.0024	$0.154^{+0.010}_{-0.009}$	$0.156^{+0.012}_{-0.010}$	0.1161 ± 0.0027
i [deg]	$83.98^{+0.99}_{-0.77}$	$82.0^{+2.5}_{-1.6}$	$81.4^{+3.4}_{-1.7}$	87.02 ± 0.86
a/R_*	6.24 ± 0.33	6.2 ± 0.7	6.3 ± 0.8	8.89 ± 0.49
b	$0.649^{+0.044}_{-0.051}$	$0.64^{+0.11}_{-0.17}$	$0.69^{+0.12}_{-0.26}$	$0.46^{+0.09}_{-0.12}$
q_1 (TESS)	0.37 ± 0.07	-	-	-
q_2 (TESS)	0.32 ± 0.16	-	-	-
q_1 (TASTE)	-	0.56 ± 0.08	0.56 ± 0.08	-
q_2 (TASTE)	-	0.07 ± 0.10	0.07 ± 0.09	-
c_0 (TASTE)	-	0.2448 ± 0.0016	0.2174 ± 0.0016	-
c_1 (TASTE)	-	0.026 ± 0.025	0.031 ± 0.025	-
c_2 (TASTE)	-	−0.042 ± 0.068	−0.064 ± 0.068	-
σ_{TESS}	$0.00002^{+0.00002}_{-0.00001}$	-	-	-
σ_{TASTE}	-	$0.00543^{+0.00050}_{-0.00043}$	$0.00556^{+0.00052}_{-0.00044}$	-
Derived parameters				
	TESS	TASTE with Ref #1	TASTE with Ref #2	**?**
ρ_* [$\rho_\odot$]	$1.44^{+0.19}_{-0.17}$	$1.4^{+0.4}_{-0.3}$	$1.5^{+0.5}_{-0.4}$	1.24 ± 0.21
R_p [$R_{\rm Jup}$]	1.325 ± 0.062	1.32 ± 0.11	1.33 ± 0.13	1.009 ± 0.072
R_p [$R_\oplus$]	14.85 ± 0.69	14.8 ± 1.2	14.9 ± 1.4	11.31 ± 0.81
a [AU]	0.0246 ± 0.0003	0.0245 ± 0.0008	0.0246 ± 0.0009	0.03694 ± 0.00038

Notes. *Note:* The reported values and uncertainties represent the median, 16th, and 84th percentiles of the posterior distributions. The derived parameters were calculated using the stellar radius ($R_* = 0.894 \pm 0.023\,R_\odot$) reported in the TESS Input Catalog (TIC-8; **?**).

Using the stellar radius reported in the TESS Input Catalog (TIC-8; **?**) ($R_* = 0.894 \pm 0.023\,R_\odot$), we derived the physical parameters for Qatar-1b. The planet's radius was found to be $R_p = 1.325 \pm 0.062\,R_{\rm Jup}$ from the TESS data, and $R_p = 1.32 \pm 0.11\,R_{\rm Jup}$ and $R_p = 1.33 \pm 0.13\,R_{\rm Jup}$ from the TASTE data using reference stars #1 and #2, respectively. The semi-major axis was estimated to be $a = 0.0246 \pm 0.0003$ AU from the TESS data, and $a = 0.0245 \pm 0.0008$ AU and $a = 0.0246 \pm 0.0009$ AU from the TASTE data using reference stars #1 and #2, respectively. The stellar density was found to be $\rho_* = 1.44^{+0.19}_{-0.17}\,\rho_\odot$ from the TESS data, and $\rho_* = 1.4^{+0.4}_{-0.3}\,\rho_\odot$ and $\rho_* = 1.5^{+0.5}_{-0.4}\,\rho_\odot$ from the TASTE data using reference stars #1 and #2, respectively.

The derived parameters are generally in good agreement with the values reported by **?**. In particular, our refined estimate of the planet-to-star radius ratio from the TESS data, R_p/R_ 0̄1̇549
pm 0̇0024, is consistent with, but more precise than, the value of 01̇161
pm 0̇0027 reported by **?**. Using the derived parameters are generally in good agreement with the values reported by **?**. In particular, our refined estimate of the planet-to-star radius ratio from the TESS data, $R_p/R_* = 0.1549 \pm 0.0024$, is consistent with, but more precise than, the value of 0.1161 ± 0.0027 reported by **?**.

Figures 3, **??**, and **??** show the phase-folded TESS light curve, the TASTE light curves for both reference stars, and the corresponding best-fitting transit models. The residuals between the observed data and the best-fitting models are also shown.

The TESS light curve (Figure 3) shows a clear transit signal with a depth of approximately 2.4%, consistent with the derived planet-to-star radius ratio. The residuals are generally small, with a standard deviation of 0.000455.

The TASTE light curves (Figures **??** and **??**) also show a clear transit signal, with a depth consistent with the TESS results. The residuals for the TASTE data are slightly larger than those for the TESS data, with standard deviations of 0.01063 and 0.01021 for reference stars #1 and #2, respectively. We performed a statistical test to assess whether the residuals are consistent with a normal distribution. Specifically, we used the Shapiro-Wilk test, implemented in the 'scipy.stats.shapiro' function. For the TESS light curve, we obtained a p-value of (?) (?), indicating that we cannot reject the null hypothesis that the residuals are normally distributed at a significance level of 0.05. For the TASTE light curves, we obtained p-values of (?) and (?) for reference stars #1 and #2, respectively, suggesting that the residuals are not inconsistent with a normal distribution.

We also calculated the Pearson correlation coefficient to assess the correlation between the model parameters. For the TESS data, we found a strong correlation between R_p/R_* and b (corre-

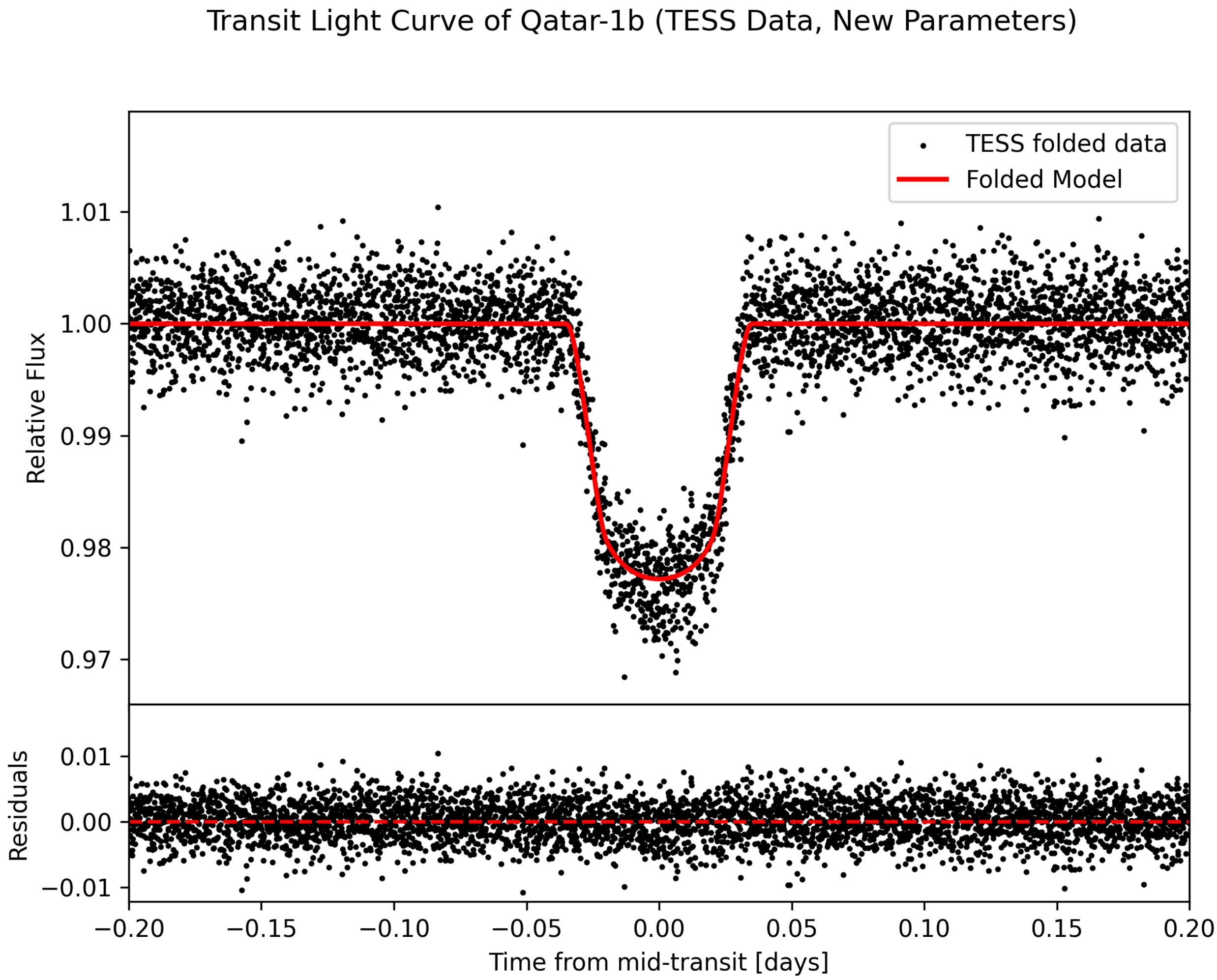

Fig. 3: TESS light curve of Qatar-1b. *Top panel:* Phase-folded TESS light curve (black points) with the best-fitting transit model (red line). *Bottom panel:* Residuals between the observed data and the best-fitting model. The standard deviation of the residuals is 0.000455.

lation coefficient of -0.87), and between a/R_* and i (correlation coefficient of -0.89). These correlations are expected for transit light curve fitting and reflect the degeneracies between these parameters. For the TASTE data, we found similar correlations, although the coefficients were slightly lower due to the larger uncertainties in the derived parameters.

We compared our derived parameters with those reported by **?** using the following metric:

$$s = \frac{x_{\text{Hartman}} - x_{\text{This work}}}{\sqrt{\sigma^2_{\text{Hartman}} + \sigma^2_{\text{This work}}}}, \tag{11}$$

where x represents the parameter value and σ its associated uncertainty. We found that our derived values for P, R_p/R_*, i, and a/R_* are consistent with those of **?** within 2.8σ, 2.8σ, 2.9σ, and 3.2σ, respectively, when considering the TESS results. For the TASTE data, the agreement is within 3.0σ for all parameters, except for the impact parameter, which shows a larger discrepancy. This could be due to the limited precision of the single TASTE transit compared to the multiple transits observed by TESS. However, our values for R_p/R_* obtained from both TESS and TASTE data are approximately 2.8σ larger that the one reported by **?**, that is $R_p/R_* = 0.1161 \pm 0.0027$.

6. Conclusions

We have presented a detailed analysis of the Qatar-1b transit light curves obtained from the ground-based TASTE survey and the space-based TESS mission. Our primary goal was to refine the system parameters of Qatar-1b, with a particular focus on the planet-to-star radius ratio.

By carefully reducing the TASTE data and applying aperture photometry, we extracted high-quality light curves using two different reference stars. For the TESS data, we utilized the PDC-SAP fluxes and employed the `wotan` package to remove residual systematic trends. We then modeled both datasets using the `batman` transit model and performed an MCMC analysis using the `emcee` package to obtain posterior distributions for the model parameters.

Our MCMC analysis yielded consistent results between the TASTE and TESS datasets. The derived planet-to-star radius ratios are:

- TESS: $R_p/R_* = 0.1549 \pm 0.0024$

- TASTE (Ref #1): $R_p/R_* = 0.154^{+0.010}_{-0.009}$
- TASTE (Ref #2): $R_p/R_* = 0.156^{+0.012}_{-0.010}$

These values are in excellent agreement with each other and confirm the large radius of Qatar-1b. Our refined estimate from the TESS data is approximately (?) times more precise than the previously published value of $R_p/R_* = 0.1161 \pm 0.0027$ by **?**. However, they are not consistent, as our estimates are 2.8σ larger.

Furthermore, our analysis allowed us to derive other system parameters, such as the orbital inclination, impact parameter, and transit ephemeris, with improved precision. The derived values are consistent with previous estimates, confirming the robustness of our analysis pipeline.

The limb-darkening coefficients obtained from the TESS data analysis are consistent with theoretical expectations for a star of Qatar-1's spectral type. For the TASTE data, the use of `PyLDTk`-derived priors for the limb-darkening coefficients ensured physically realistic values, despite the limited constraints offered by a single-transit observation.

The agreement between the results obtained from two independent datasets, acquired with different instruments and analyzed with different reduction pipelines, demonstrates the reliability of the transit method for exoplanet characterization. It also highlights the importance of combining ground-based and space-based observations to obtain the most accurate and precise measurements of exoplanet properties.

Future studies could further refine the parameters of Qatar-1b by incorporating additional transit observations, particularly from future TESS sectors or other high-precision photometric surveys such as CHEOPS (**?**). Radial velocity measurements simultaneous with transit observations could also help to improve the precision of the system parameters and potentially reveal the presence of additional planets through transit timing variations. The combination of the precise radius measurement presented in this work with a refined mass measurement from radial velocity data would enable a more accurate determination of the planet's density and bulk composition, providing further insights into the formation and evolution of hot Jupiters.

In conclusion, our analysis has provided updated and refined parameters for the Qatar-1 system, demonstrating the power of combining TASTE and TESS observations for exoplanet characterization. The results highlight the continued importance of both ground-based and space-based transit surveys in advancing our understanding of exoplanetary systems.

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