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Transit light curve fitting of Earth-like exoplanet candidate Kepler-452b

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ABSTRACT

We report an analysis of the light curve data of Kepler-452, a system that possibly contains a single transiting Earth-like in planet in the habitable zone. We fit the relative radius, impact parameter, and stellar density of the exoplanet candidate Kepler-452b using a Markov Chain Monte Carlo (MCMC) method informed by previous results in Jenkins et al. (2015). Our results lean towards a smaller size for Kepler-452b and a higher density for the star it orbits compared to literature. We additionally obtain a posterior distribution for the equilibrium temperature and radius of Kepler-452b using stellar parameters from the DR25 catalog (Mathur et al. 2017). Our results place Kepler-452b as very likely within the habitable zone temperature criterion 207.5K $< T_p <$ 320.4K but with only a small probability $R_p < 1.23 R_\odot$, a naive indicator for rocky composition. We find a 13% probability of the Kepler-452b being both rocky and in the habitable zone. Generally, our findings support Kepler-452b's most likely classification as a super-Earth located within the habitable zone of its star.

1. INTRODUCTION

The Kepler-452b was first described by Jenkins et al. (2015) as a possibly rocky super-Earth orbiting within the habitable zone of its host star. At the time, the reported period of $384.843^{+0.007}_{-0.012}$ days and radius of $1.63^{+0.23}_{-0.20}\ R_\odot$ placed Kepler-452b as the small, transiting exoplanet with the longest period yet discovered. Later analysis by Mullally et al. (2018) and Burke et al. (2019) has shed considerable doubt on the detection confidence of Kepler-452b and other long period, small exoplanet candidates discovered by Kepler. They found that Kepler-452b does not meet the 99% confidence threshold for Kepler detections due to a systematic false alarm probability.

In this paper, we work under the assumption that Kepler-452b is a real planet and not a false alarm. We adopted the transit timing parameters reported in Jenkins et al. (2015) without modification. We used a transit period of 384.843 days and set the first transit time at MJD 55147.980.

1.1. *Outlier detection and detrending*

The first observation (at MJD 55091.468) in the provided data file is an extreme outlier with a relative flux value of 0.964, much lower than the second lowest observation at 0.9987. This data point is likely an error in pre-processing and was not considered in any analysis. We looked for additional outliers in the data using a rolling median with a five-observation window and a 3σ threshold. This search marked 1.2% of the observations as outliers. While this is more than would be expected from a Gaussian sample, we did not find a strong case for the marked points as requiring removal after visual inspection and opted to select a detrending method robust against outliers instead of masking them outliers.

We performed non-parametric detrending using a time-windowed median locator, which is easy to implement and has been found to perform well in benchmarks against other methods (Hippke et al. 2019). We chose a window length of three times the reported transit duration of 10.63 h.

1.2. *Transit model fitting*

We use the `batman` Python package to model transit light curves (Kreidberg 2015). We assume a circular planetary orbit with the timing parameters from Jenkins et al. (2015). We used a quadratic stellar limb-darkening law with parameters supplied by Prof. Kipping.

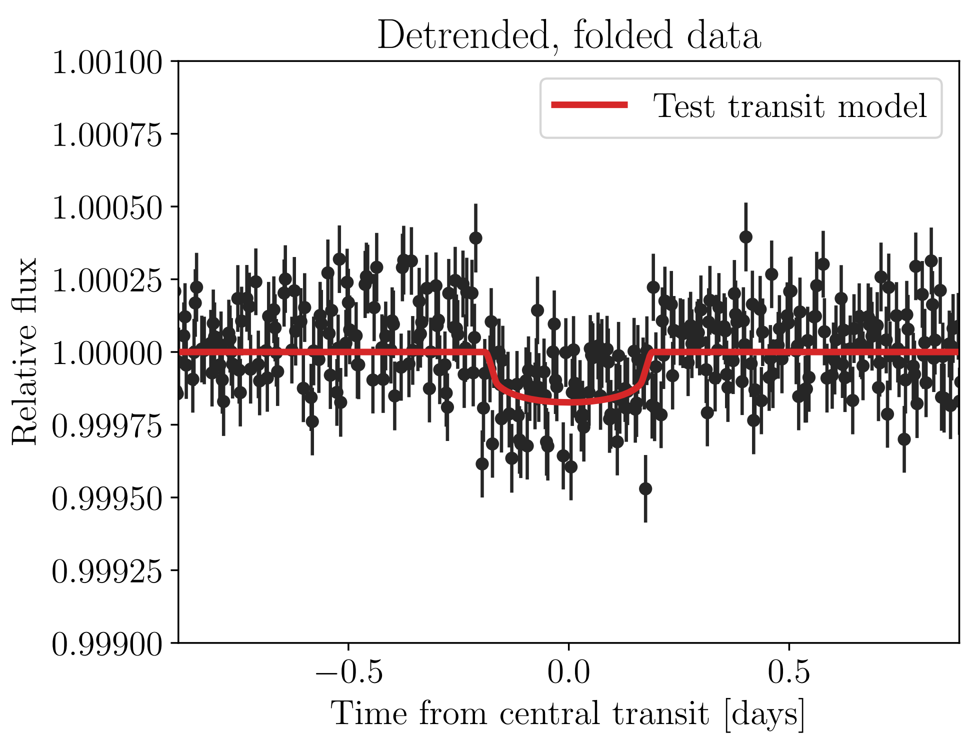

Figure 1. The detrended light curve for $Kepler-452$ folded around the transits of $Kepler-452b$. The "Test transit model" was created with the parameters reported by Jenkins et al. (2015) using `batman`.

We fit the transit model to the data with MCMC using the `emcee` Python package (Foreman-Mackey et al. 2013). We considered three model parameters: the relative radius of the planet (R_p/R_*), the impact parameter ($b = a\cos i/R_*$), and the stellar density ($\log\rho_*$). Uniform priors are adopted for each parameter, with b constrained to positive numbers. We compute the χ^2 log-likelihood for each model proposal. We ran an 8 walker ensemble for $2^{16} = 65536$ samples per walker, removing the first 1000 samples of burn in.

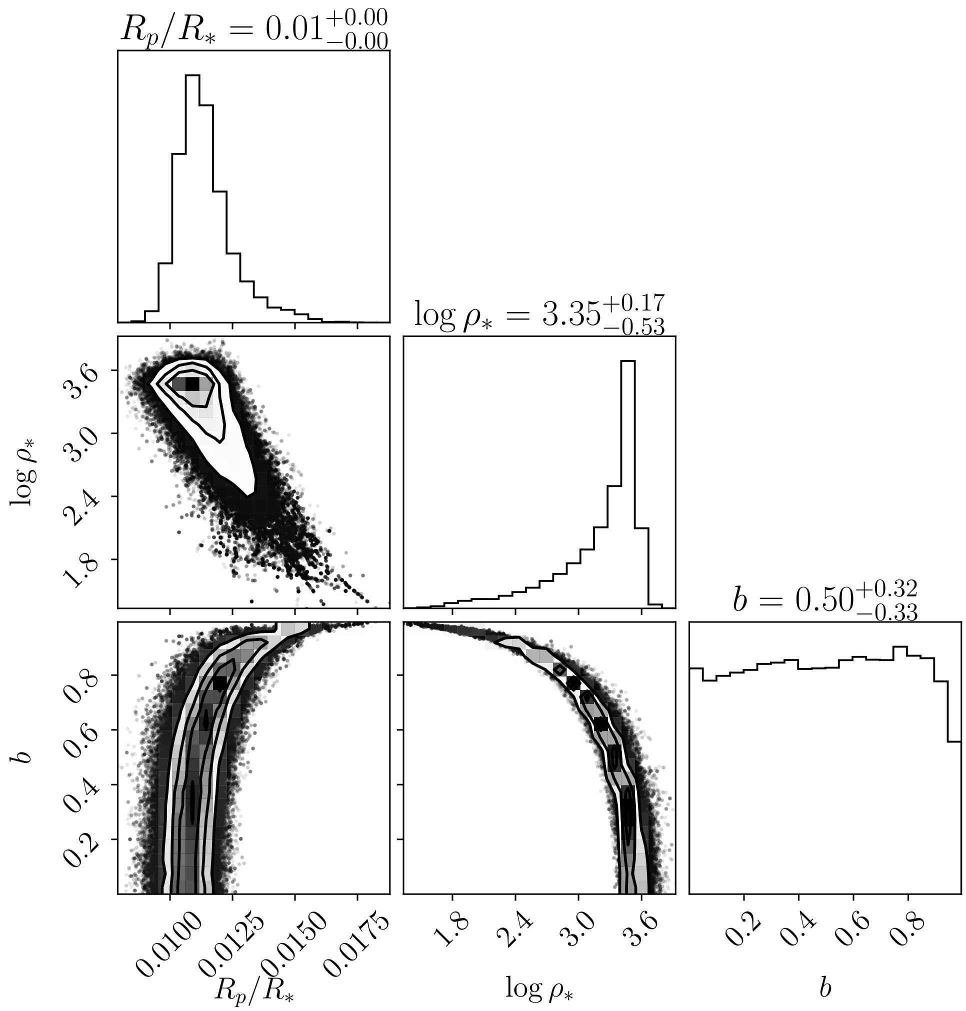

Figure 2. Corner plot of posteriors for R_p/R_*, $\log\rho_*$, and b for Kepler-452b from `emcee`. There are a total of $8\times(2^{16}-1000) = 516,288$ samples represented. The full result for R_p/R_* is $0.0112^{+0.0011}_{-0.0008}$. Figure created with `corner.py` (Foreman-Mackey 2016)

2. RESULTS

The center of our posterior distribution has a higher stellar density and smaller relative planetary radius than reported by Jenkins et al. (2015). Our distribution displays a long tail to the bottom right with increased planetary radii and much lower stellar densities. The values in Jenkins et al. (2015) lie on the bottom right

Parameter	Jenkins et al. (2015)	This work
R_p/R_*	$0.0128^{+0.0013}_{-0.0006}$	$0.0112^{+0.0011}_{-0.0008}$
$\log\rho_*$ [kg m^3]	$2.92^{+0.17}_{-0.11}$	$3.35^{+0.17}_{-0.53}$
b	$0.690^{+0.160}_{-0.450}$	$0.50^{+0.32}_{-0.33}$

Table 1. Parameters of the orbit of $Kepler-452b$ and its host star. Comparison between this work and Jenkins et al. (2015)

edge of our 2-sigma, or 86% containment, region on the 2D histogram (middle of left column of Figure 2).

The impact parameter b is poorly constrained because the entire sample space corresponds to inclination angles of nearly 90 degrees, or edge-on from the telescope's perspective. Our result of $b = 0.50^{+0.32}_{-0.33}$ agrees the value $b = 0.690^{+0.160}_{-0.450}$ from Jenkins et al. (2015) with little differentiation between $b = 0.2$ and $b = 0.8$.

2.1. *Rocky and habitable?*

We calculate joint posterior distributions for Kepler-452b's equilibrium temperature and radius using the DR 25 stellar posteriors sample for KIC 8311864 (Mathur et al. 2017).

The stellar radius reported in DR2 is $0.798^{+0.15}_{-0.075} M_\odot$ (Mathur et al. 2017). This value disagrees significantly with the other solutions for the stellar parameters listed on the NASA Exoplanet Archive https://exoplanetarchive.ipac.caltech.edu/overview/Kepler-452b, which have a consensus around 1.1 $R_\odot$. Jenkins et al. (2015) attribute the discrepancy to an overstated surface gravity measurement in the KIC. To better match the literature, we apply a corrective factor of $f_R = 1.1/0.8 = 1.375$ to the stellar radii posteriors from DR2.

We create 1,000,000 samples combining one random sample from our MCMC results and one random sample from the stellar posterior for T_* and R_*. We calculate the planet's radius as $R_p = f_R R_* \left(R_p/R_*\right)$ and its temperature as

$$T_p = T_* \sqrt{\frac{R_\odot}{2a_p}} \tag{1}$$

where a_p is the semi-major axis of the orbit.

We classify the planet as laying in the habitable zone if $207.5\text{K} < T_p < 320.4\text{K}$ and the planet as rocky if $R_p < 1.23 R_\odot$.

We find that 89% of our samples lies within our habitable zone, but only 11% of our samples match the rocky planet criterion. Only 13% of samples match both. Our value for Kepler-452b's radius, $R_p = 1.43^{+0.25}_{-0.18}$, has some overlap with the reported value $1.63^{+0.23}_{-0.20} R_\oplus$ (Jenkins et al. 2015). The proportion of samples in the "rocky" radius range is reduced by the correction for the star's radius.

$P(x)$	H	$\bar{H}$	Total
R	**0.13**	0.00	0.13
$\bar{R}$	0.75	0.11	0.87
Total	0.89	0.11	1.00

Table 2. Probabilities that Kepler-452b lies in the habitable zone (H), is rocky (R), or both with the correction for Kepler-452b's stellar radius applied. Based on our 1,000,000 samples of the MCMC results in this work and the DR25 stellar posterior.

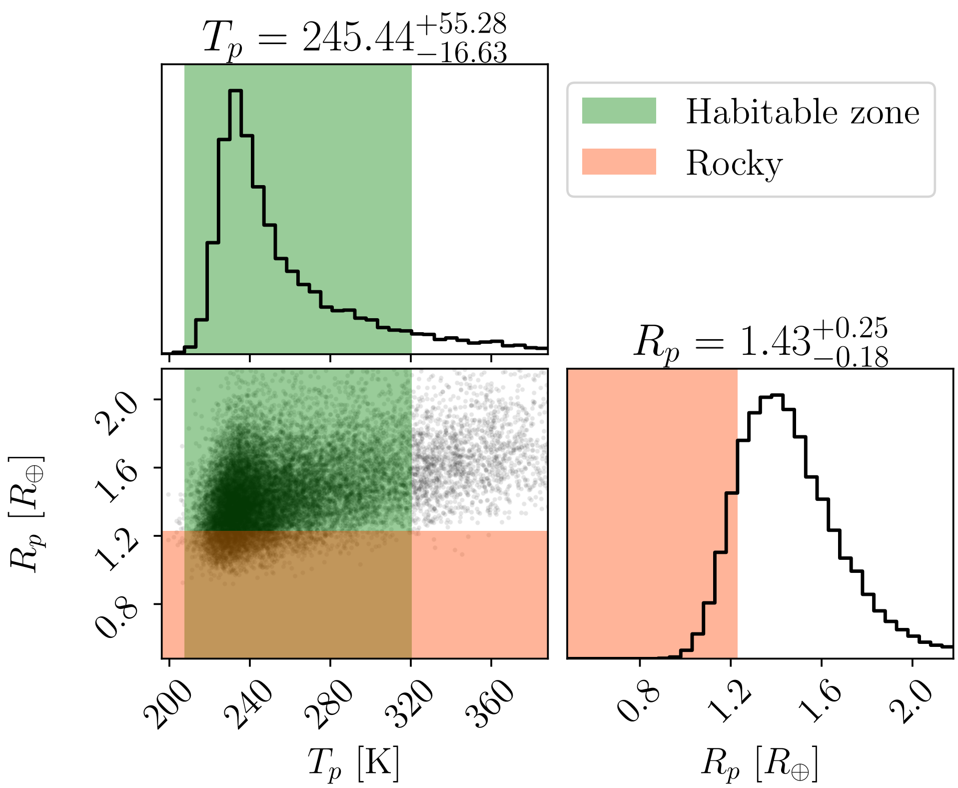

Figure 3. Corner plot of our joint T_p, R_p distribution with our habitable zone and rocky planet criteria highlighted. A sample of 50,000 points is shown in the bottom left scatter plot.

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