Proceedings of CONF-CIAP 2026 Symposium: International Conference on Atomic Magnetometer and Applications
DOI: 10.54254/2753-8818/2026.HZ29348

An Alternative Method to Confirm the Tidal Inspiral of Hot Jupiter Kepler-1658b

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Abstract. The tidal decay phenomenon of hot Jupiters has been a significant research topic. Multiple hot Jupiters have been observed by missions including the Kepler space telescope and the Transiting Exoplanet Survey Satellite (TESS) to confirm the existence of this phenomenon. In this study, we focused on Kepler-1658b, the first exoplanet discovered by the Kepler mission. Instead of the `exoplanet` package used in previous studies, we used a method based on `lmfit` to analyze light curve data from Kepler and TESS and calculated a period decay rate of $\dot{P} = 132 \pm 29\mathrm{ms\ year}^{-1}$, confirming the existing suggestion that this phenomenon exists for this hot Jupiter.

Keywords: Exoplanet astronomy, Exoplanet evolution, Exoplanet tides, Hot Jupiters, transits

1. Introduction

Hot Jupiters, gas giant exoplanets that are close to their host planets, constitute a major portion of exoplanets that we have discovered and have been widely observed by multiple exoplanet observation missions, including Kepler [1] and the Transiting Exoplanet Survey Satellite, also known as TESS [2], as well as ground-based observatories. The orbital decay of hot Jupiters due to tidal effects is an important topic of study in the field of exoplanetary science and is closely related to the ultimate fate of hot Jupiters. It is predicted by theory that the orbital radius of these planets shrinks due to tidal effects, eventually leading to the total destruction of the planets [3].

This orbital decay phenomenon has been proposed to exist in multiple hot Jupiters, including WASP-12b [4], TOI-2109b [5], and Kepler-1658b [6]. More suspicious targets can be found in [7]. However, the phenomenon is usually subtle and difficult to observe with great certainty on a reasonable timescale.

The focus of this article is Kepler-1658b (KOI-4.01), the first exoplanet discovered by the Kepler mission. According to [8], Kepler-1658b is a hot Jupiter ($M_{\mathrm{p}} = 5.88 \pm 0.47 M_{\mathrm{J}}$, $R_{\mathrm{p}} = 1.07 \pm 0.05 R_{\mathrm{J}}$) orbiting a subgiant star ($M_{\star} = 1.45 \pm 0.06 M$, $R_{\star} = 2.89 \pm 0.12 R$) in an orbit with a short period of approximately 3.85 days. Previous studies have suggested that tidal inspiral exists for the planet. [6] used data collected by the Kepler and TESS missions, as well as ground-based observations by Palomar/WIRC [9], and concluded the existence of the phenomenon, claiming to have ruled out other potential explanations including line-of-sight acceleration and apsidal precession. A more recent study,

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[10] included data in four new TESS sectors and further confirmed this result, suggesting a decay rate of $\dot{P} = -(3.423 \pm 0.458) \times 10^{-4}\mathrm{s\ day}^{-1}$.

In this article, we applied a different method for processing light curve data of the Kepler-1658 system collected by the Kepler and TESS missions than using `exoplanet` [11] as in [6]. In Section 2. we presented the observational data and stellar parameters we collected for analysis. In Section 3. we presented our method of fitting models to the raw data. In Section 4. we determined the exact period decay rate. In Section 5. we compared our study and previous studies on the system. In Section 6. we concluded the existence of the tidal decay phenomenon and suggested further research.

2. Data

2.1. Kepler and TESS Data

We analyzed both Kepler and TESS observations of Kepler-1658b. The Kepler data consist of 15 quarters of both long (30 minutes exposure) and short (1 minute exposure) cadence light curves, consistent with those mentioned by [6]. TESS data for Kepler-1658 were obtained during sectors 41, 54, 55, 74, 75, 81, and 82 of the mission. Data from the first three sectors was included in the analysis by[6]. A brief Research Note by [10] describes a timing analysis of the TESS data from sectors 74, 75, 81, and 82. Here we analyze all of the Kepler and TESS data together and in more detail than presented by [10].

2.2. Collecting Stellar Parameters

In addition, the system parameters measured by [8] were obtained from the NASA Exoplanet Archive, including the mid-transit time t_c, the planet-to-star radius ratio $R_p/R_\star$, the impact parameter b, the period p, and the scaled semi-major axis $a/R_\star$. These values are necessary to constrain transit light-curve models and ensure physical consistency in our fits.

Table 1: A table showing the stellar parameters obtained from [8] and the corresponding values.

Stellar Parameters	Value
t_c	2455005.924100
$R_p/R_\star$	0.0369
b	0.9471
P	3.849372784
$a/R_\star$	4.04

Unlike previous studies, which typically produced only one “averaged” transit time per quarter or sector, we chose to measure the midpoint of each individual transit that was observed. This approach increased the number of timing measurements and allowed for finer quality control, although the statistical uncertainty in each timing measurement is necessarily enlarged.

3. Method

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3.1. Fitting Transit Light Curves

We modeled single transits using `lmfit`, adopting system parameters from [8] as initial inputs. The orbital period P was fixed, assuming no variations, while all other parameters were allowed to vary. Examples of fitted transits from both Kepler and TESS are shown in Figures 1–2. While Kepler light curves exhibit clear transit signals, the TESS data display shallower trends, leading to larger uncertainties in derived t_c values.

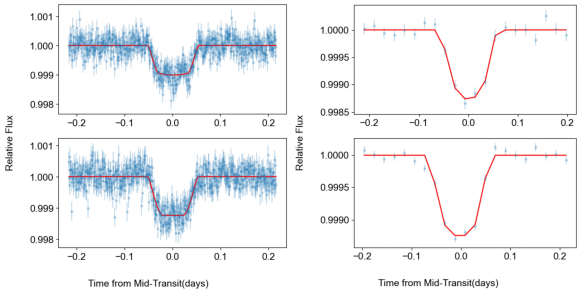

Figure 1: Examples of some transit times among Kepler data. The left half shows the light curve and the best-fit line of Kepler Quarter 2 and 7 (two quarters that are short cadence), while the right half shows that of Kepler Quarter 8 and 9 (two quarters that are long cadence). We picked the first transit of each quarter as examples.

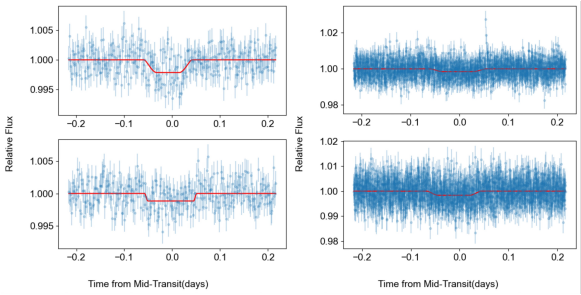

Figure 2: Examples of some transit times among TESS data. The left half shows the light curve and the best-fit line (red curve) of TESS Sector 41 and 54, while the right half shows that of TESS Sector 81 and 82. We picked the first transit of each sector as examples. As shown in the graphs, the trend of TESS data is not very obvious, producing larger uncertainties.

Ultimately, we compared our results to the data in [6], finding that the data are highly consistent, it can be precise to two or three decimal places. However, since we were calculating the transit time for all transits of every quarter instead of the middle transit of one single quarter, the individual transit times have larger uncertainties than the quarter-averaged transit times presented by [6].

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Table 2: Transit times of Kepler-1658b obtained from Kepler and TESS data. The table lists the transit time (BJD), the timing uncertainties, and the cycle number, where the first cycle stands for the second transit in Kepler SC Quarter 2

Transit Time (BJD)	Uncertainties	Cycle Number
2454955.882	±0.00119	-13
2454971.285	±0.00127	-9
2455005.926	±0.00078	0
2455098.309	±0.00222	24
2455190.695	±0.00139	48
2455283.080	±0.00163	72
2455467.849	±0.00113	120
2455571.782	±0.00289	147
2455644.917	±0.00431	166
2455837.389	±0.00460	216
2455937.471	±0.00268	242
2456018.309	±0.00269	263
2456210.779	±0.01084	313
2456322.409	±0.00150	343
2456395.548	±0.00102	362
2459424.996	±0.00388	1148
2459771.443	±0.00535	1240
2459802.232	±0.00387	1246
2460321.889	±0.00410	1381
2460345.001	±0.00484	1387
2460510.515	±0.00417	1430
2460537.458	±0.00584	1437

3.2. Linear and Quadratic Models

In our study, we employed two models to analyze the transit times. The linear model assumes a constant period:

$$t(n)_{\text{linear}} = t_0 + nP \tag{1}$$

where t_0 is $t_{c,\text{reference}}$, n is the orbit number, and P is the orbital period [4].

The quadratic model allows a decaying period:

$$t(n)_{\text{quadratic}} = t_0 + nP + \frac{1}{2}\left(\frac{dP}{dn}\right)n^2 \tag{2}$$

After obtaining all transit times, we excluded data points with large uncertainties. We then plotted a graph containing t_c and orbit number n, where

$$n = \text{round}\left[\frac{t_c - t_{c,\text{reference}}}{P}\right] \tag{3}$$

and we chose $t_{c,\text{reference}} = 2454955.88215929$ as the first transit time among our data. We first fit the linear model to the data points and calculated the expected transit times, comparing them with the

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observed values to obtain time deviations:

$$\Delta t = t(n)_{\text{linear}} - t_{c,\text{initial}} \tag{4}$$

Meanwhile, we also fit the quadratic model for comparison (Fig. 3).

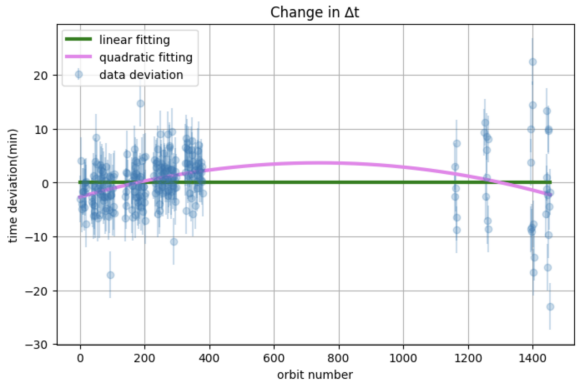

Figure 3: The $O - C$ diagram with both linear and quadratic models fitted.

4. Results

After calculating the χ^2 for both models, we found that the quadratic model fit better than the linear model.

Table 3: Comparison of χ^2 values between the linear and quadratic fitting models.

Type of Fitting	χ^2
Linear Fit	373
Quadratic Fit	345

The quadratic fit exhibited a parabolic trend in the $O - C$ diagram, indicating that the orbital period of Kepler-1658b is decreasing. From the coefficients of the quadratic fit, we calculated the period decay:

$$\dot{P} = -132.205 \pm 29.410 \text{ms year}^{-1} \tag{5}$$

This value was very close to the result reported by [6], who found

$$\dot{P} = -131 \pm 20 \text{ms year}^{-1} \tag{6}$$

However, the uncertainty of our results was greater, and the reason to this is still unclear. Although we have more uncertainty on each data point, we have more data points, so they should be able to cancel each other out.

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5. Discussion

5.1. The Reason Of Greater Uncertainty

As mentioned above, in the processing of TESS data, we choose to use all windows from each sector in both Kepler data and TESS data as the original data for final fitting. However, in previous papers, they only selected one window with better observation data from each sector. Therefore, the volume of original data we choose for fitting is much larger, which leads to greater randomness in our data. This randomness may be the reason for the greater uncertainty in the orbital decay rate we obtain.

5.2. The Differences Between Different Data Processing Methods

From one perspective, a certain degree of reduced fitting (the previous paper using for ensuring our results were robust to choices in modeling methodology) can be applied to all known observational data; however, by incorporating all observational data into the original dataset(our method) used for the fitting curve in the final t_c calculation, it can be ensured that the final result $\dot{P}$ is supported by a larger body of original data, making the result more reliable.

6. Conclusion

This study used light curve data of the Kepler-1658 system recorded by the Kepler and TESS missions and attempted to confirm the results in [6] and [10], using a method based on `lmfit` rather than the `exoplanet` toolkit in previous studies. The study derived a period decay rate of $\dot{P} = -132 \pm 29\text{ms year}^{-1}$, which is consistent with previous results. Given the unlikeliness of other explanations, including line-of-sight acceleration and apsidal precession, as explained in [6], we may reasonably suggest that the phenomenon of tidal inspiral exists within this system.

For further research, we suggest continued light curve observations of the system by both space and ground-based telescopes, as the subtle tidal effect is easier to detect and confirm with greater precision with data on a longer timescale. Moreover, we encourage searching for similar phenomena within other systems with hot Jupiters based on current observational data. The large value of the inverse scaled semimajor axis $R_\star/a$ in these systems make them potential candidate for valuable discoveries.

Acknowledgments

We are extremely grateful to the CIS staff for organizing the program, as well as Prof. Joshua Winn and TA Yunchuan Zhang for instructing us throughout our research process. We also thank the Shanghai Jiao Tong University (Qibao Campus) for hosting our class. Finally, we deeply appreciate Dr. Shreyas Vissapragada at Carnegie Observatories for personally helping us gain a better understanding of his method of analyzing observations of the Kepler-1658 system.

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