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Distinctions between TESS and Kepler data of KIC 8462852 and criticism of the circumsolar ring hypotheses

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Abstract. KIC 8462852, an F3 main sequence star, has been observed to undergo deep light curve dips whose origin remains unknown. Since the discovery of these deep dips in 2016, numerous hypotheses have been proposed, including but not limited to dust clouds, a family of disrupted comets, and circumstellar gas. In this paper, the possibility of the circumsolar ring hypothesis is explored by evaluating the flux change of surrounding stars and calculating the possible thickness of the ring. This work also analyzes Kepler data and the new TESS data of KIC 8462852, which presents a symmetric transit-like dip that has never been observed. Speculating this is a planet-star transit. This work yields a transit period of 427 days. The analysis of the latest data set provides further evidence for the study and may weaken some predicted periods and hypotheses.

Keywords: KIC 8462852, Boyajian’s Star, TESS, periodicity, Circumsolar ring.

1. Introduction

KIC 8462852(Boyajian’s Star) has long been discussed since it was detected by the *Kepler* mission and was announced in 2016 by Boyajian et al. [1]. The *Kepler* data of KIC 8462582 feature erratically timed dips with different depths, shapes, durations, and intervals. Various theories have been proposed to explain the anomalous dip patterns, including the following: circumstellar dust [2], inspiral of a planetary body [3], solar system obscuration [4], absorption by the interstellar medium [4], and an exomoon [5]. In addition, diverse periodicities have been proposed for the dips, ranging from 48.4 to 1574 days [6]. Succeeding the *Kepler* mission, TESS (Transiting Exoplanet Survey Satellite) was launched on April 18, 2018. TESS is an all-sky survey mission discovering exoplanets around nearby bright stars [7]. So far, KIC 8462582 has been observed in 5 sectors of TESS, including two dips. This paper examines the *Kepler* and TESS data of KIC 8462582 and its surrounding stars. This work analyzed a) periodicity in Kepler and TESS data, b) possible cause of the dips, and c) a model for TESS data.

2. Analysis of Kepler data

KIC 8462852 was observed in quarters 0 to 17 of the Kepler mission, yielding continuous data of its light curve with 30-minute sampling. Periodicity of transits We normalized the data and analyzed them

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more extensively than previous studies, encompassing 18 dips shown in Figure 1 (D123, 140, 216, 260, 359, 502, 573, 659, 792, 993, 1001, 1143, 1205, 1335, 1460, 1519, 1568 observed in the Kepler time series data). It is detectable that there are 15 dips with similar amplitudes that range from ~0.98 to ~0.999 and three dips with significantly larger dips.

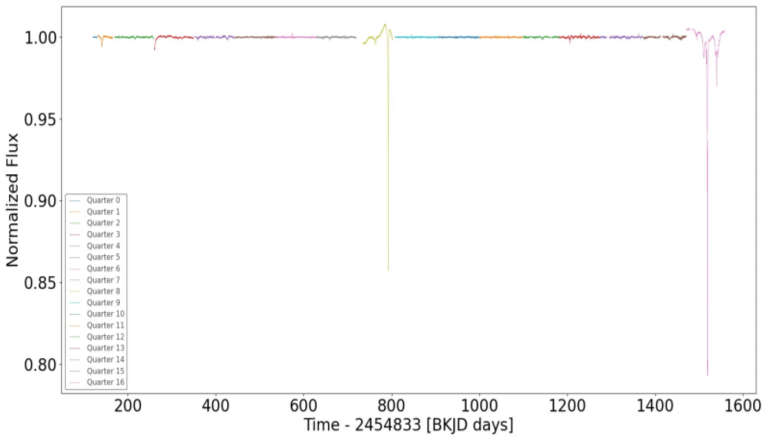


Figure 1. Holistic graph of the normalized flux-time of KIC 8462852.

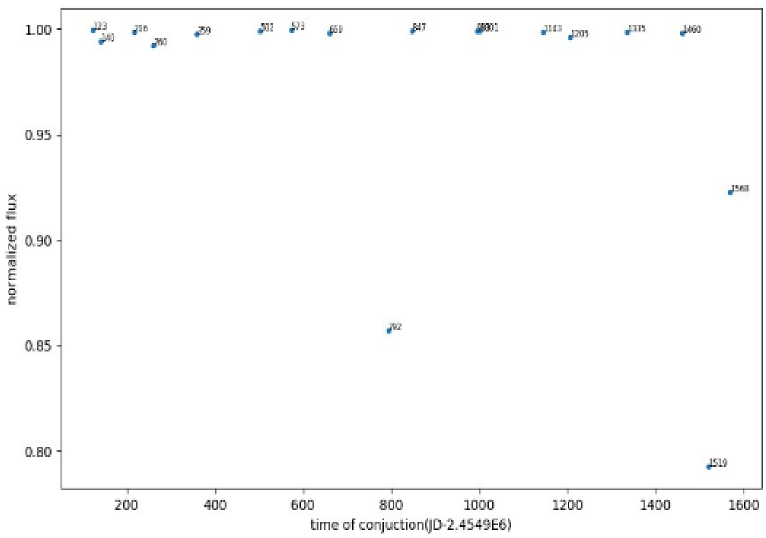


Figure 2. Transit time- normalized flux.

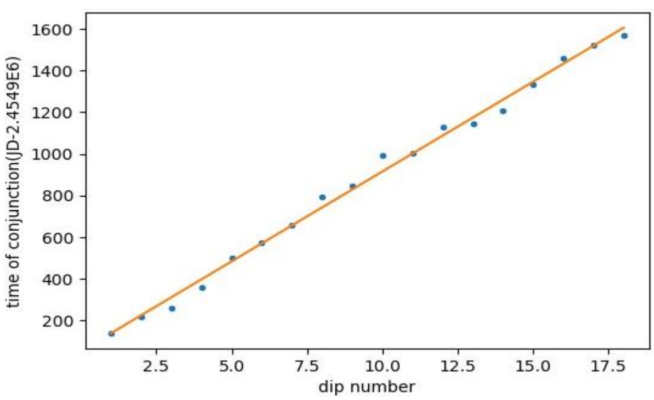


Figure 3. Transit times and a fitting line.

This work obtains the time of the points with smallest normalized flux in each observable dip as the time of the conjunction of the corresponding transit. In Figure 4, we present the transit times and a fitting line, which shows an overall periodicity of 86.26 days. Since the measurement uncertainties of the times of minimum light are unclear, it is difficult to calculate the χ^2. So, we calculated and plotted the differences between the fitted transit time and the measured transit time (see Figure 2). As shown in Figure 3, the timing deviations are comparable to the proposed period itself - so, there is not much, if any, evidence for periodicity based on this type of analysis.

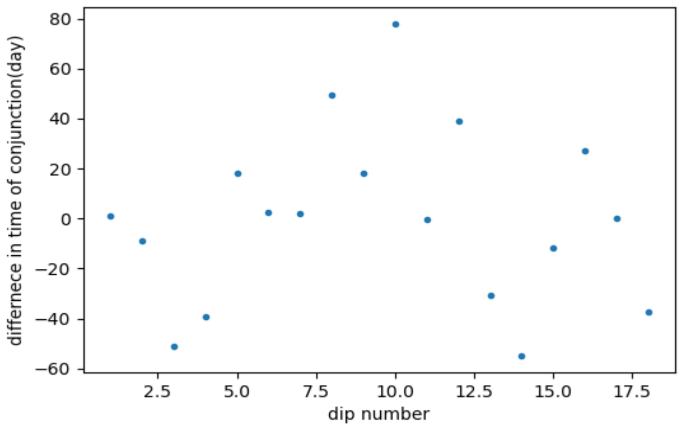


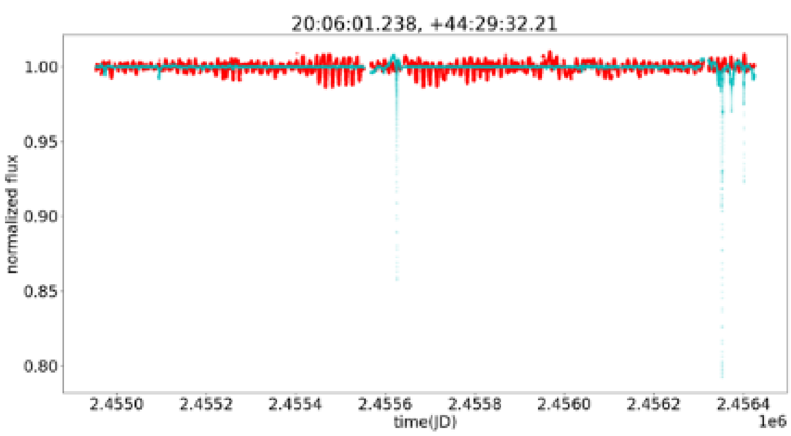
Figure 4. Differences between the fitted transit time and the measured transit time.

2.1. Periodicity of star rotation and pulsation

According to [1], the ~0.88 d signal in the light curve due to the star's rotational period can be verified by the Short-Term Fourier Transform (STFT) of the Kepler light curve and the projected rotational velocity.

2.2. Analysis of the cause of dips in Kepler data: test on Circumsolar Ring Hypothesis

If a cloud ring exists between the telescope's sight of view and Boyajian's Star, surrounding stars are also likely to experience similar variations in dips [4]. Hence, we pick four surrounding stars, that are observed in the same time period as KIC 8462852, with coordinates 20h 06m 01.238s, $+44^{\circ}29'32.21''$; 20h 06m 14.844s, $+44^{\circ}25'37.74''$; 20m 06h 21.209s, $+44^{\circ}30'52.06''$ and 20h 06m 23.640s, $+44^{\circ}27'38.38''$. Angular separation is also calculated with values of 0.0547°, 0.0299°, 0.0605° and 0.4472°, respectively. Figure 5 (a) (b) (c) (d) shows plots of normalized light curves compared with that of Boyajian's Star. An overlapping steady line indicates no similar trend.



(a)

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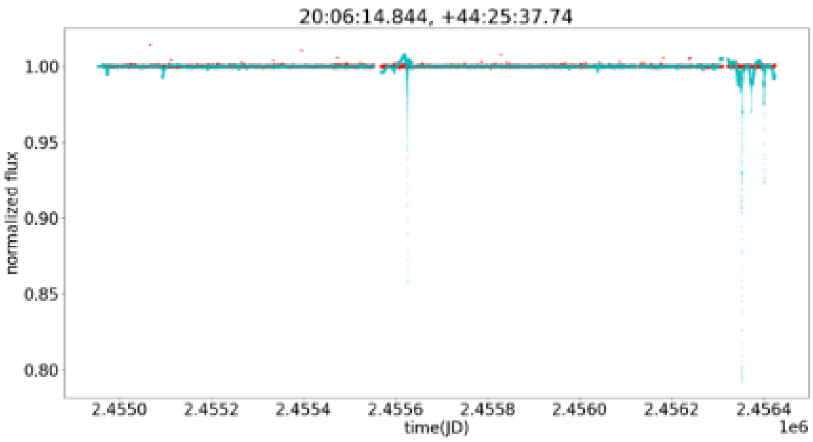
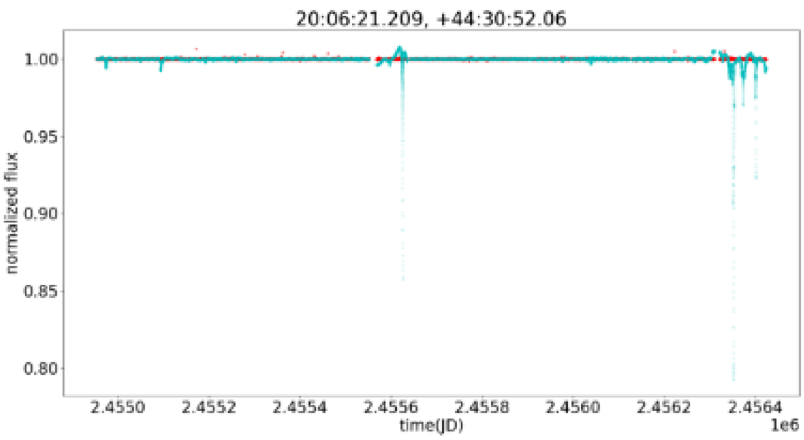
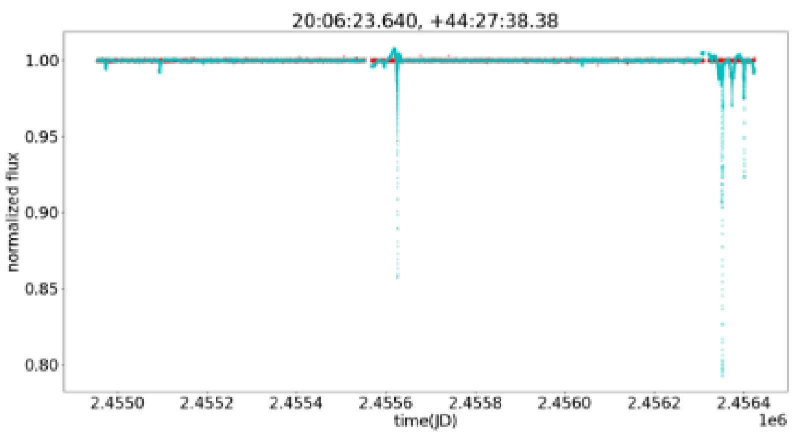


(b)



(c)



(d)

Figure 5. (a) Star at $+44^{\circ}29'32.21''$06m 14.844s, $+44^{\circ}25'37.74''$ compared with KIC 8462852 (blue). **(b)** $+44^{\circ}25'37.74''$ Star at 20h compared with KIC 8462852. **(c)** $+44^{\circ}30'52.06''$ 23.640s $+44^{\circ}27'38.38''$compared with KIC 8462852. **(d)**$+44^{\circ}27'38.38''$Star at 20h 06m compared with KIC 8462852.

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These four stars have an average photometric variability amplitude of 1.38%, 0.216%, 0.112%, and 0.321%, respectively. In comparison, the average dip variation for Boyajian's Star is 2.65%, much greater than selected stars. In this case, we do not consider the flux fluctuation above 1.00 as we only compare the depth of each dip. Hence, for each case, we take the average dip variation as:

$$\Delta F_{avg} = 1 - \frac{1}{F_{min}} \tag{1}$$

Taking the increase in flux into account, the average change variation is 2.41%, 1.61%, 0.776%, and 0.668%, respectively, and 2.91% for Boyajian's Star. Still, the value is much smaller than Boyajian's Star.

Therefore, this paper concludes that for the case shown in Figure 5(b)(c)(d), all show a steady flux fluctuation and do not bear any resemblance to that of Boyajian's star.

For the case shown in Figure 5(a), the stars, KIC 8462696(20h 06m 01.238s, $+44^{\circ}29'32.21''$), shows relative greater fluctuation compare with the others, but no significant dip is shown. This may be because the star is in a different evolutionary stage, such as a pulsating star. Further investigation is needed to determine the cause of the fluctuation.

3. Analysis of TESS data

To gain greater precision when processing the TESS data, this paper used data with a 120s exposure time-calibrated by the TESS Science Processing Operations Center (SPOC) pipeline.

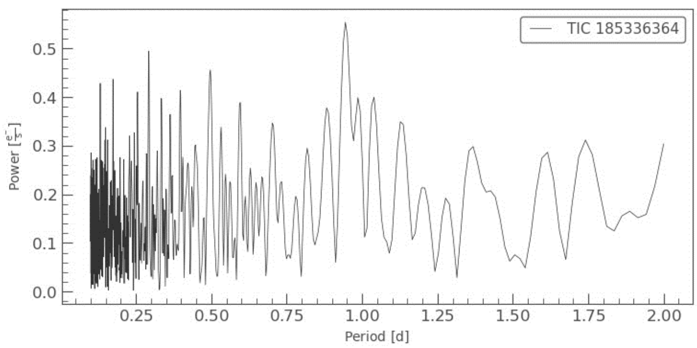
3.1. *Periodicity of transits*

Two dips are statistically significant in the TESS data (see Figure 6(c)). The first with an amplitude of ~1.05%, the second with an amplitude of ~2%. No dip of similar amplitude is recorded, and neither of these two dips is consistent with the period calculated from *Kepler* data. Because of the symmetry pattern and flat bottom of the second dip, this dip resembles the dip created by planetary transit. Thus, we used the model of planetary transit to fit the model and calculated its expected orbital period (shown as the following), assuming a 90-degree angle of inclination.

$$T \approx T_{0\sqrt{1-b^2}},\ \tau \approx \frac{T_0 k}{\sqrt{1-b^2}} \tag{2}$$

$$T_0 \equiv \frac{R_* P}{\pi a} \approx 13hr \left(\frac{P}{1yr}\right)^{1/3} \left(\frac{\rho_*}{\rho_\odot}\right)^{-1/3} \tag{3}$$

The calculation yielded an expected orbital period of ~470.058 days. Though the assumption is subject to a factor-of-a-few uncertainty due to the unknown orbital inclination and eccentricity, this work can conclude from the estimation that Kepler can detect similar events if it has periodicity. However, no event was found according to this periodicity.



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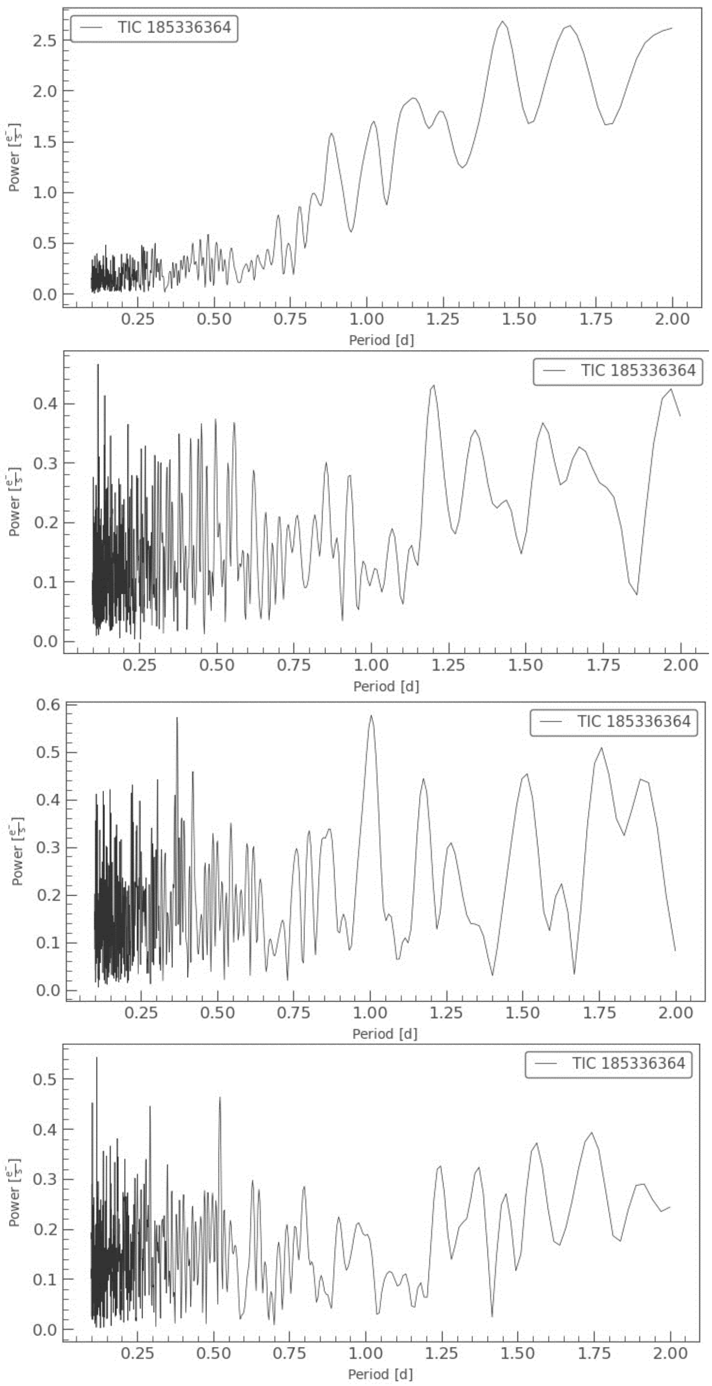
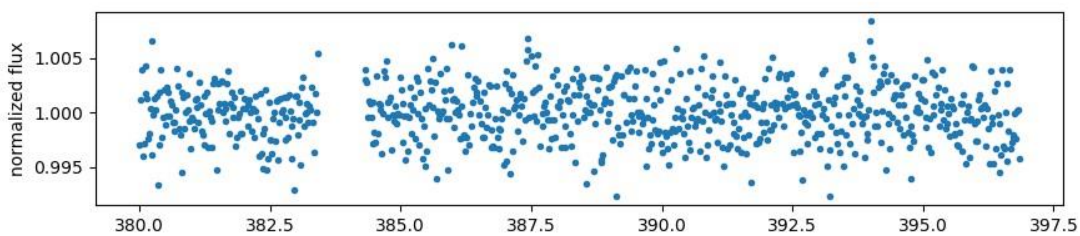


(a)



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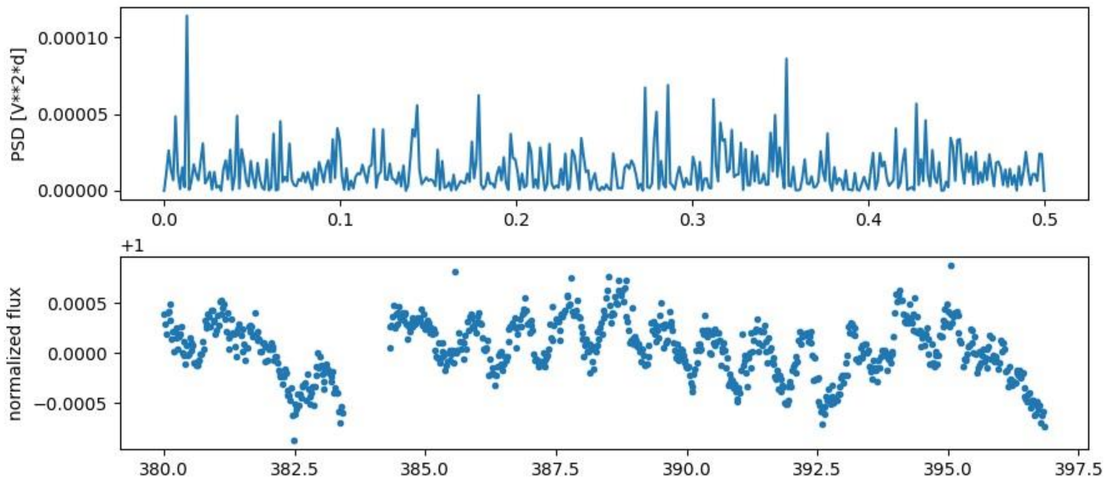
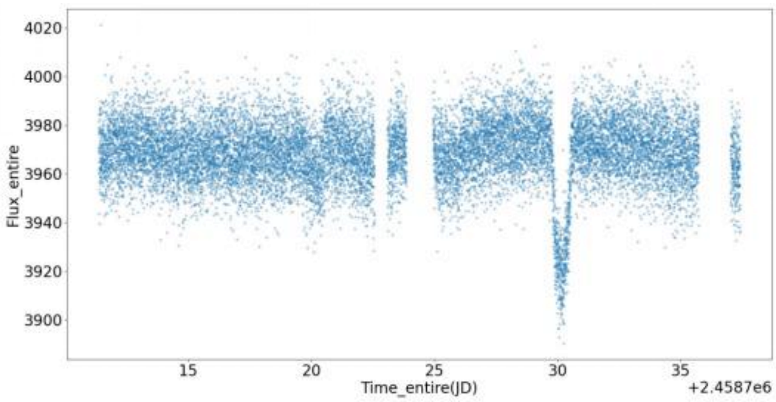


(b)



(c)

Figure 6. (a)FFT on TESS data. **(b)** Processed Kepler data with the same uncertainty as TESS data. **(c)** TESS light curve.

3.2. Periodicity of star rotation and pulsation

To test for ~0.88 d periodicity in the TESS light curve, we performed FFT (Fast Fourier Transform) on TESS data. We cut out the period range of 0-2 days (See Figure 6(a)). However, no significant peak at ~0.88 days is found. To test whether we could have detected the same type of signal that was seen in the Kepler data, we added noise with the same uncertainty of TESS data to the *Kepler* data where ~0.88 periodicity has already been detected and performed FFT with the same procedure (See Figure 6(b)). As a result, periodicity is still undetected. Therefore, even if the same signal that was seen in the Kepler data was also present during the TESS observations, the precision of the TESS data is insufficient to have allowed for its detection.

3.3. Analysis of the cause of dips in TESS data

This paper used the model of a transiting planet in [8] to fit the data. Limb-darkening is taken into account according to the quadratic limb-darkening law [9]. The Levenberg-Marquadt method was used for optimization and error estimation. This paper mainly investigated the second dip which is more distinctive in depth and shape. First, we fitted the entire dip (See Figure 7) using the previously described method, and we identified an amplitude of ~2% and a duration of ~0.904 days. Second, this paper fitted the two halves of the dip separately, and identified a significantly symmetric shape and a flat bottom that resembles the pattern of a planet transit (See Figure 8).

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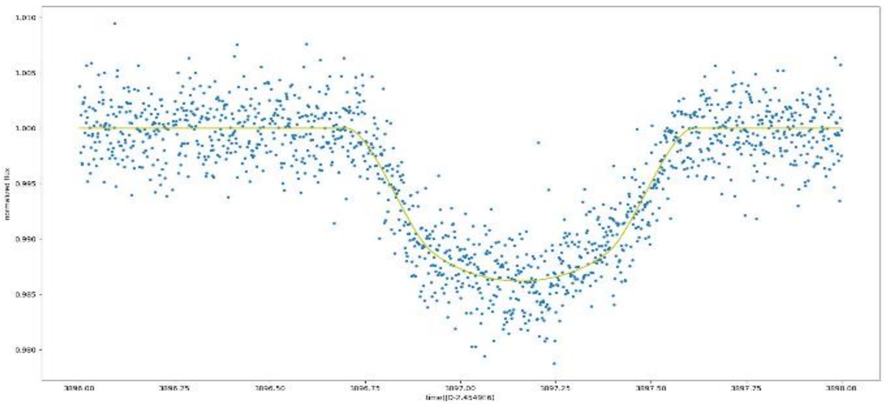

Figure 7. Data and fitting line the entire dip.

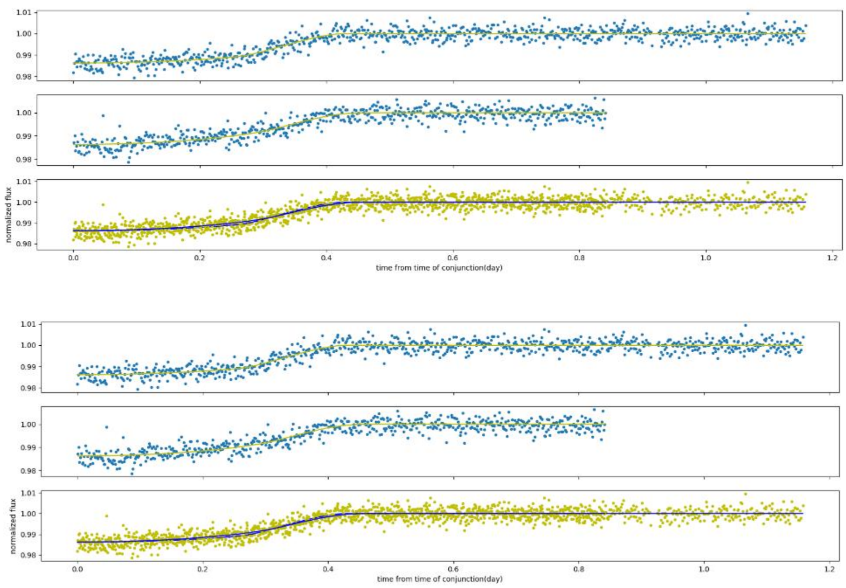

Figure 8. Two halves of the dip and their fitting lines.

3.4. Test on Circumsolar Ring Hypothesis

The model estimates the thickness of the potential ring, using the equation [10]:

$$\delta z \approx \frac{1}{2}\left(\frac{\delta t}{\frac{P}{2\pi}}\right)^{2} a \sin\theta \approx \frac{1}{2}\left(\frac{\delta t}{\frac{P}{2\pi}}\right)^{2} \sin\beta_{star}\, AU \qquad (4)$$

Where a is the circular orbit radius of the ring, t is the half width hald maximum (HWHM) of the dip, P is the oribtal period of the platform, here we use the period of TESS P = 351d ("TESS - Transiting Exoplanet Survey Satellite," 2016), and β = 62.1898° for KIC 8462852. The most significant dip detected by TESS has t ~ 0.904d. The calculated δz for the dip occurred in sector 15 is $\sim 10^{7}$, contradicting the smallest value $\delta z \sim 10^{8}$ concluded from Kepler data. However, it is possible that δz may change over the years. This work also tests on the predicted period of ~ 1y. Based on the TESS dip analyzed above, no 1y period is shown. The Levenberg-Marquardt method shows a period of ~ 470 days. This may be caused by the patchy and thin structure of the ring [10] $\delta z \sim 10^{7}$, which is smaller than the value concluded from the Kepler data. It may also be caused by the random motion of uneven distributed materials in the ring - group of objects contribute to the dip may experience a more elliptical orbit. Considering the highly symmetric shape of the dip, it weakens the circumsolar ring hypothesis. Patchy and uneven distribution of matter should produce asymmetric dips with flux variation. As seen in Kepler data, most dips consist of three small dips (see Figure 9) No record of symmetric and flat-bottom dips are found in Kepler data.

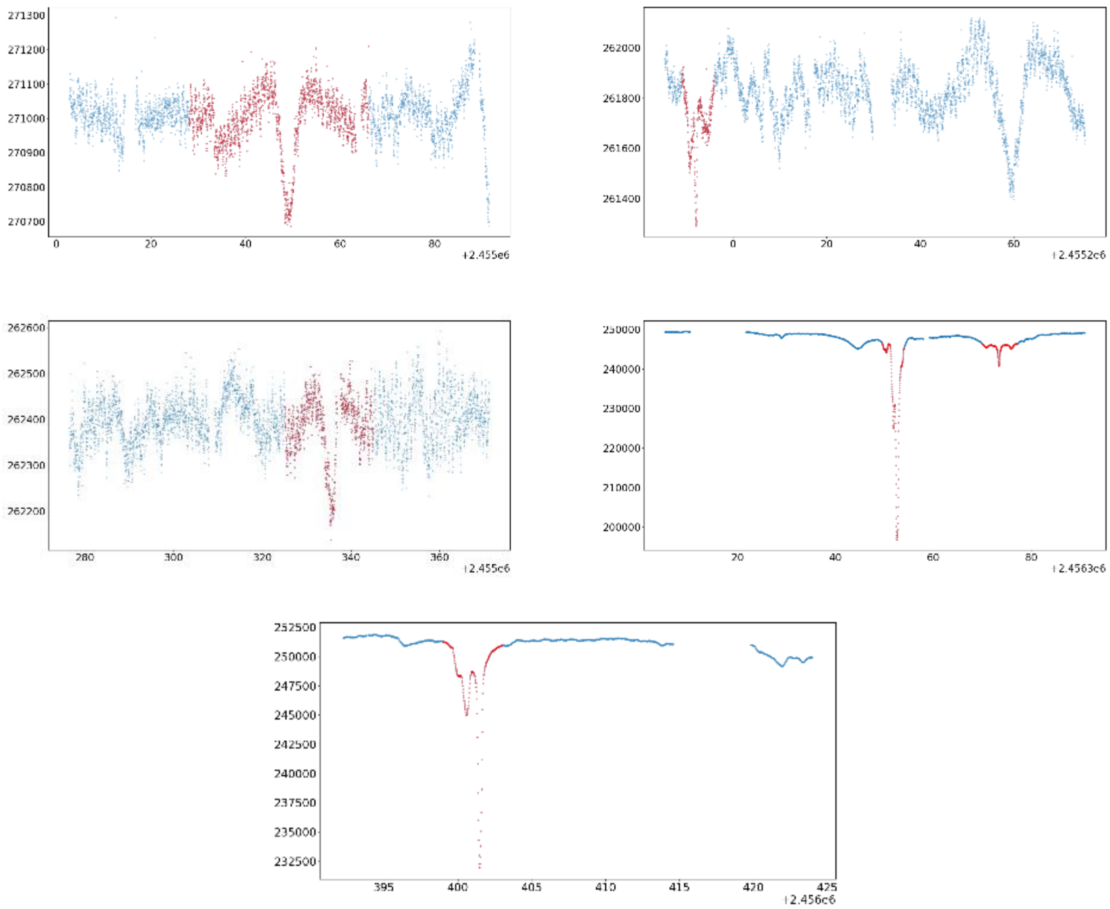

Figure 9. Examples of dips in Kepler data.

In fact, this paper suspects the dip may be a planet - star transit. This paper fits the geometry of planet - star transit [8], considering quadratic limb-darkening, and a reasonable curve is shown in Figure 7. This paper plots the residual and calculate the probability such χ^2 will observe P~ 0.850(see Figure 10). To confirm whether this is an exoplanet, more data detected similar dip is required as this is the first occurrence of a transit-like dip.

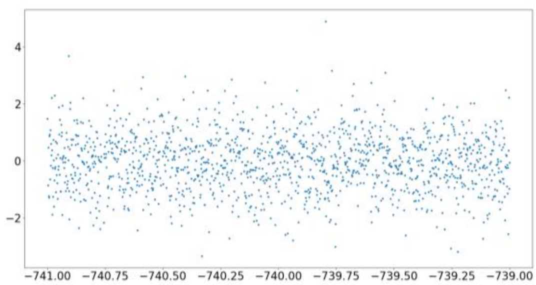

Figure 10. Residual of the fitted line.

4. Conclusion

This paper analyzed Kepler and TESS data of KIC 8462852 to yield possible periods of the dips by using a fast Fourier transform. Also, we fitted planet – star transit model to the dip in TESS data, raising the possibility of the presence of an exoplanet. To test the previous circumsolar ring hypothesis, we calculated the flux change of nearby stars compared with KIC 8462852 and expected δz.

Outcome 1: The Kepler data as well as TESS data, shows a lack of periodicity. The precision of TESS is incapable of detecting the periodic signal due to star rotation and pulsation.

Outcome 2: By using the method of detecting flux change of nearby stars, little evidence supported that the unusual flux variation is due to the circumsolar ring.

Outcome 3: The second dip in TESS data can possibly be explained by a transiting planet with a period of order one year, although no other transits were detected on that timescale.

KIC 8462852 will continue to be observed again in about one year. Then, the new data should be carefully examined. In particular, if a similar flat-bottom, symmetric dip is observed, it may provide more evidence on the nature of the cause and probability of having an exoplanet. Also, it would be helpful if more precise and careful test could be conducted using circumsolar ring model, such as performing mathematical modeling. This may provide evidence for circumsolar ring hypothesis and surrounding environment. Exploring stars around Boyajian's Star will also be helpful if similar star is found.

Acknowledgment

Yichen Lan and Jiayang Xu contributed equally to this work and should be considered co-first authors.

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